Particle Acceleration and Gamma-ray Emission from Starburst Galaxies

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Starburst galaxy M82 – APOD - Image credit: Daniel Nobre

Why Starburst Galaxies?

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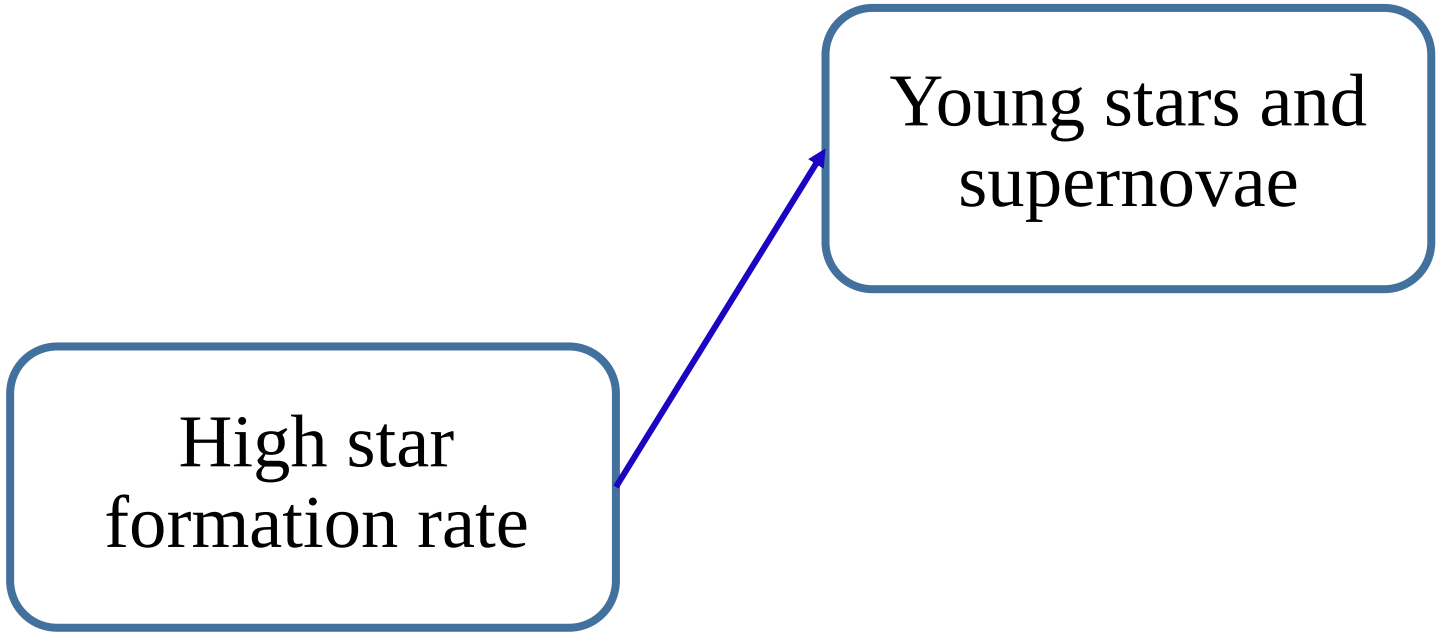
High star formation rate

Why Starburst Galaxies?



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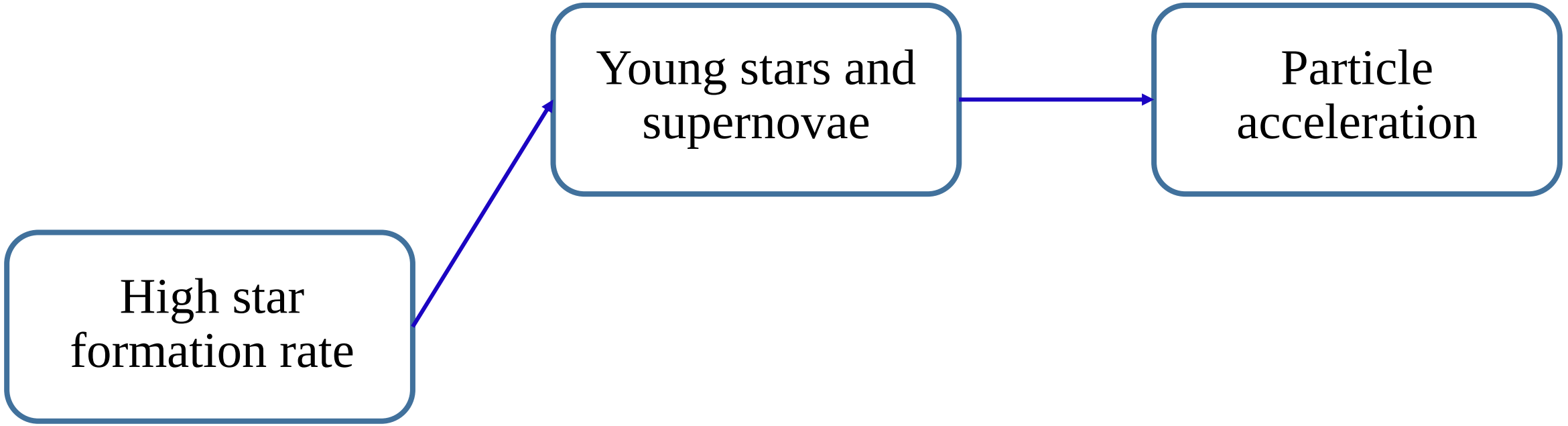

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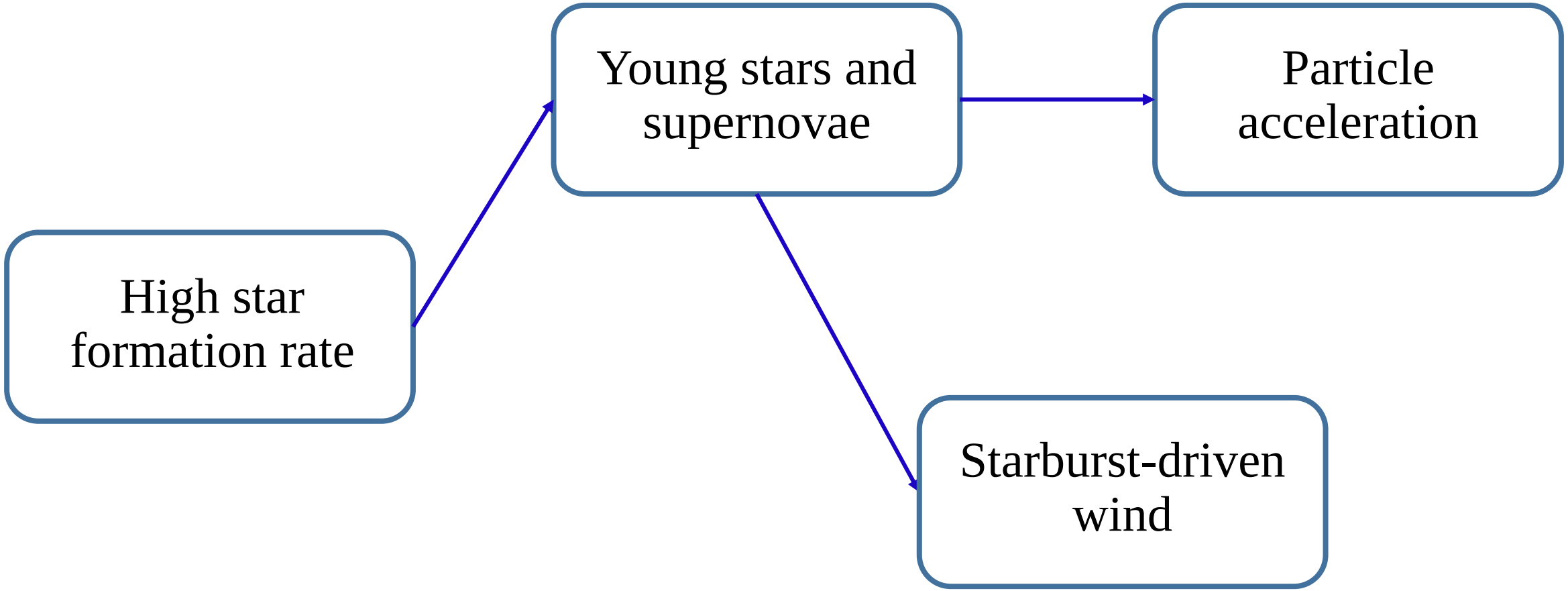

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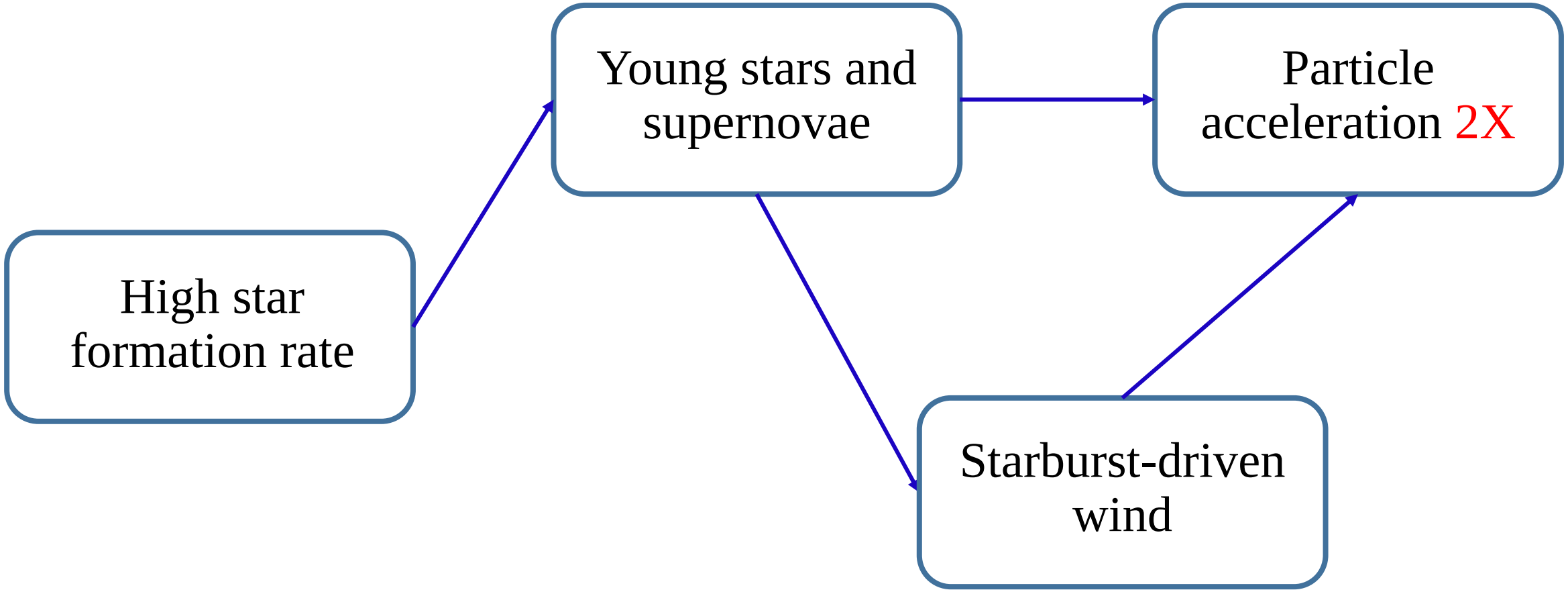

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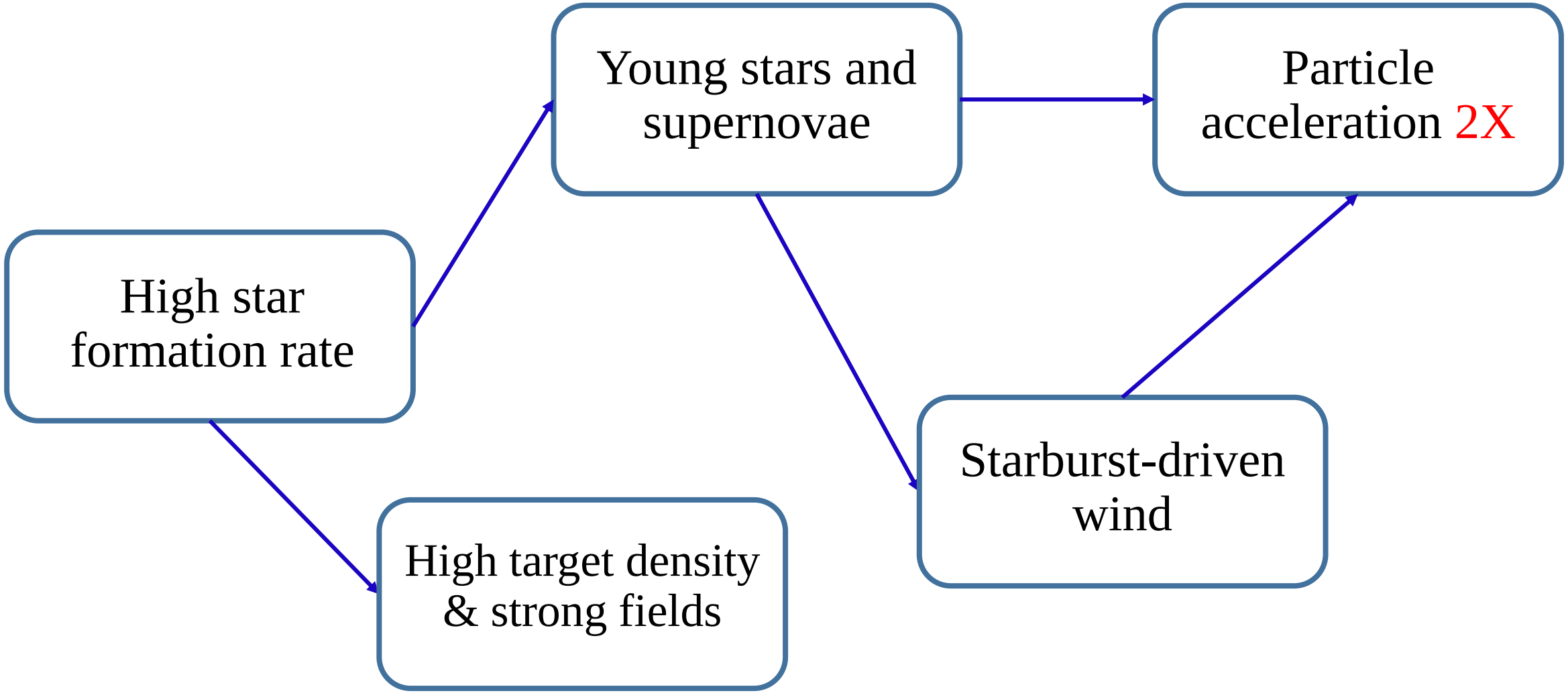


Why Starburst Galaxies?

Particle acceleration 2X

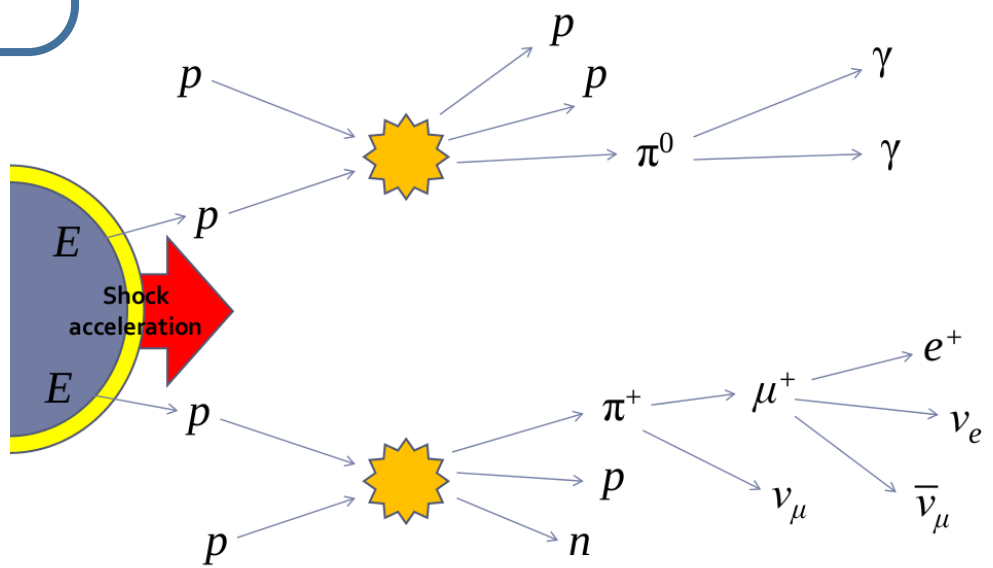
High target density & strong fields

Why Starburst Galaxies?

Particle acceleration 2X

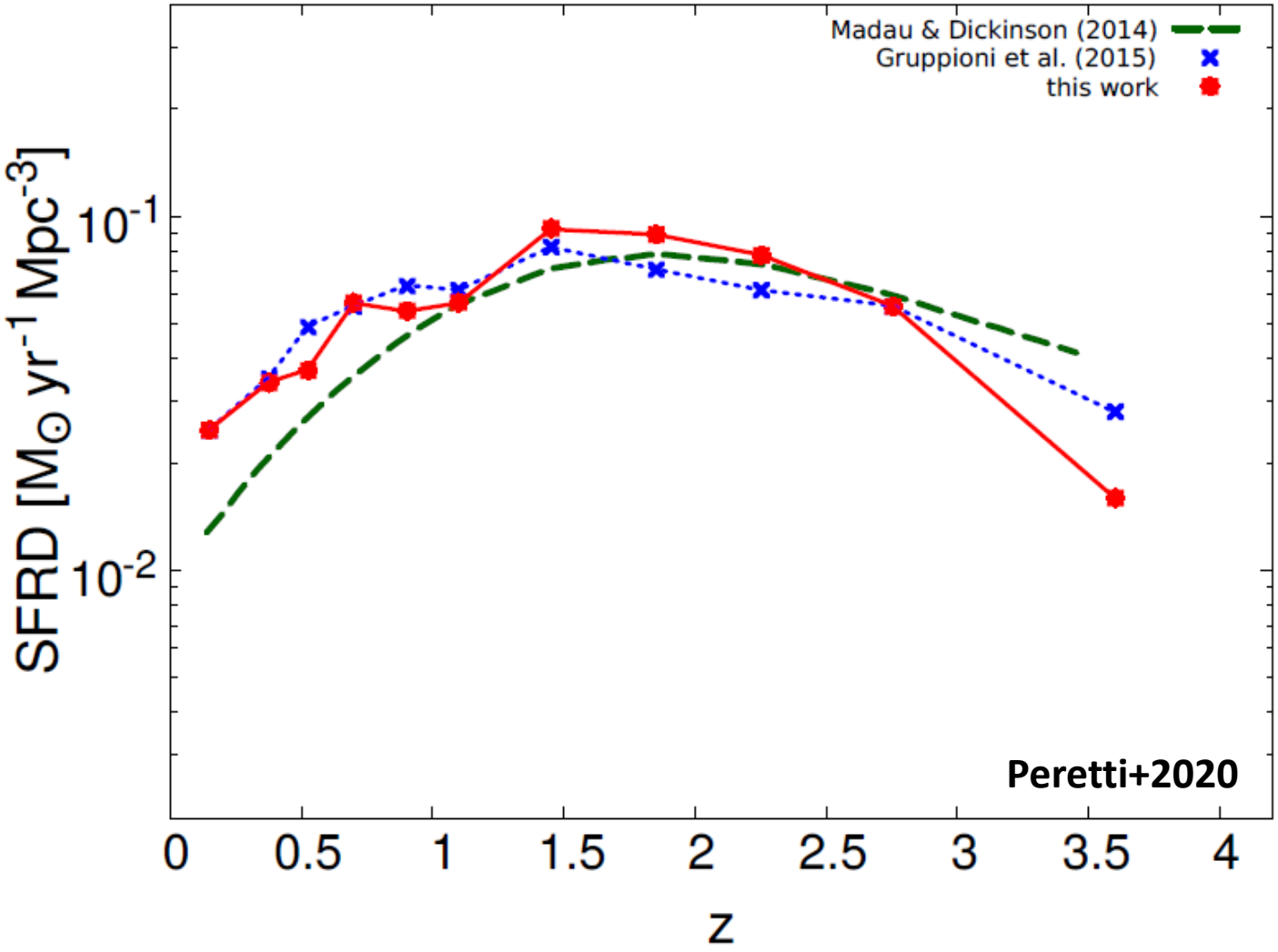
Interactions

High target density & strong fields



Website: http://www.astro.wisc.edu/~gvance/index.html

Another reason to study Starbursts



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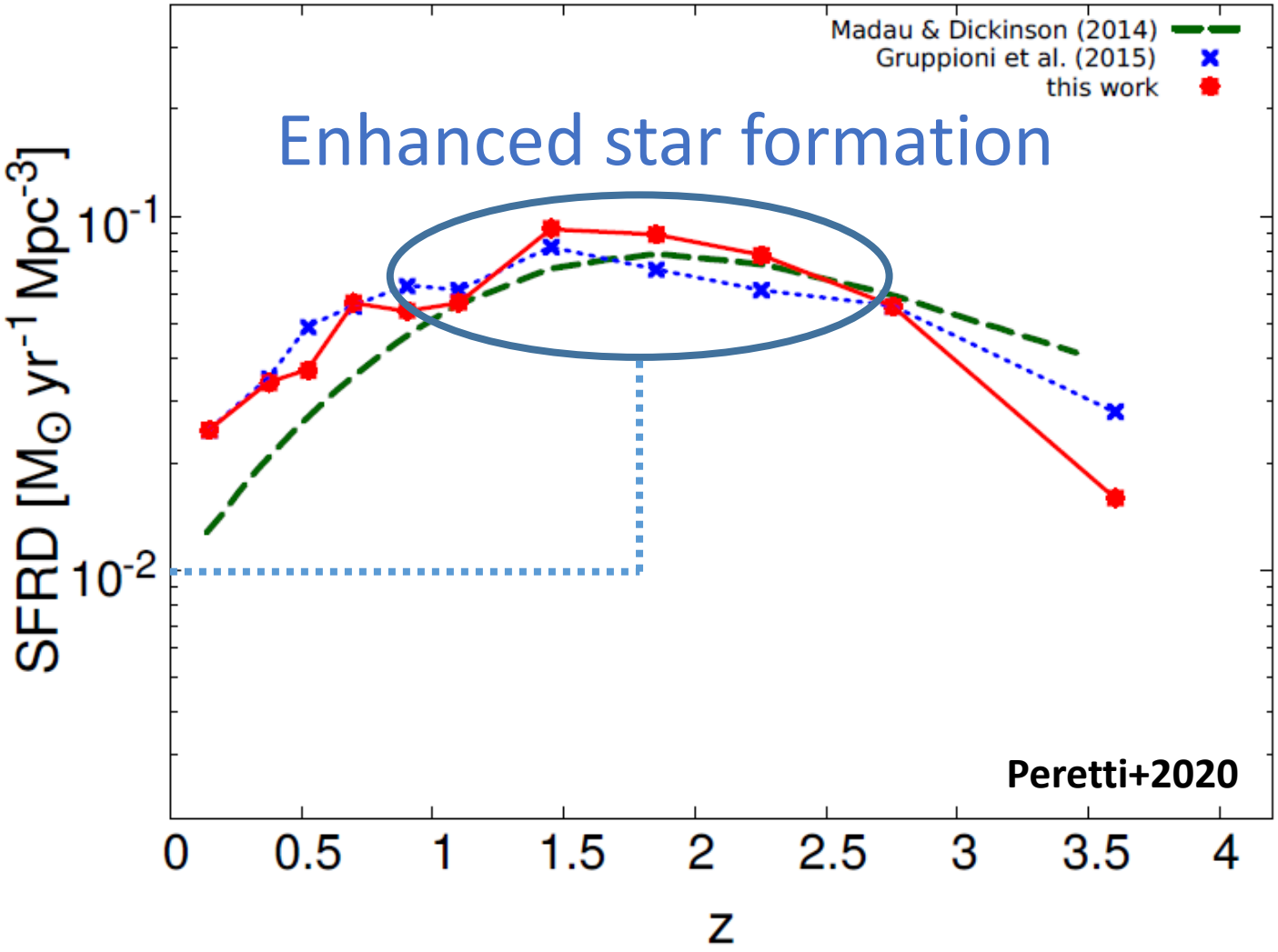

Motivations for studying Starburst Galaxies

- Several acceleration sites (SBN + wind)
- High rate of interactions → Calorimetry?
- Numerous at high redshift → Diffuse flux?

Outline

- Observations of Starburst Galaxies
- Particle Transport in Starburst Nuclei
- Acceleration and transport in starburst-driven winds
- Diffuse emission from Starburst Galaxies

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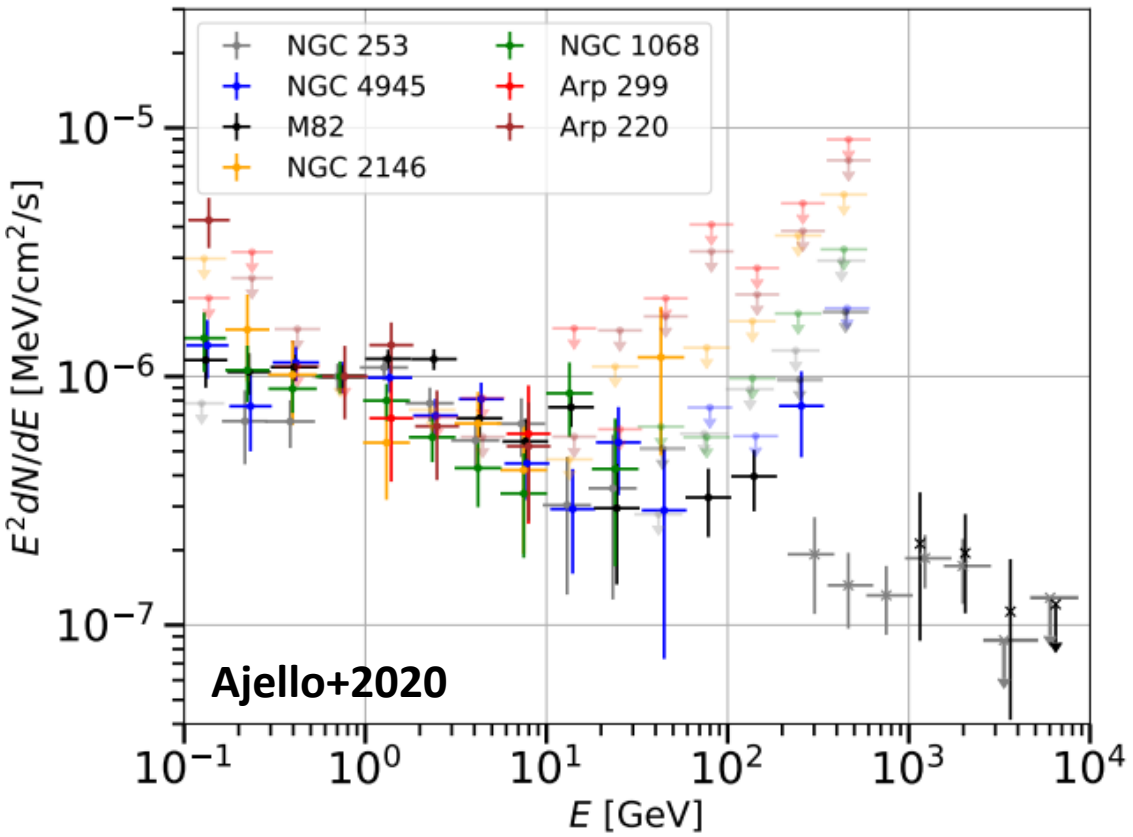
Observation of Starburst Galaxies - Gamma



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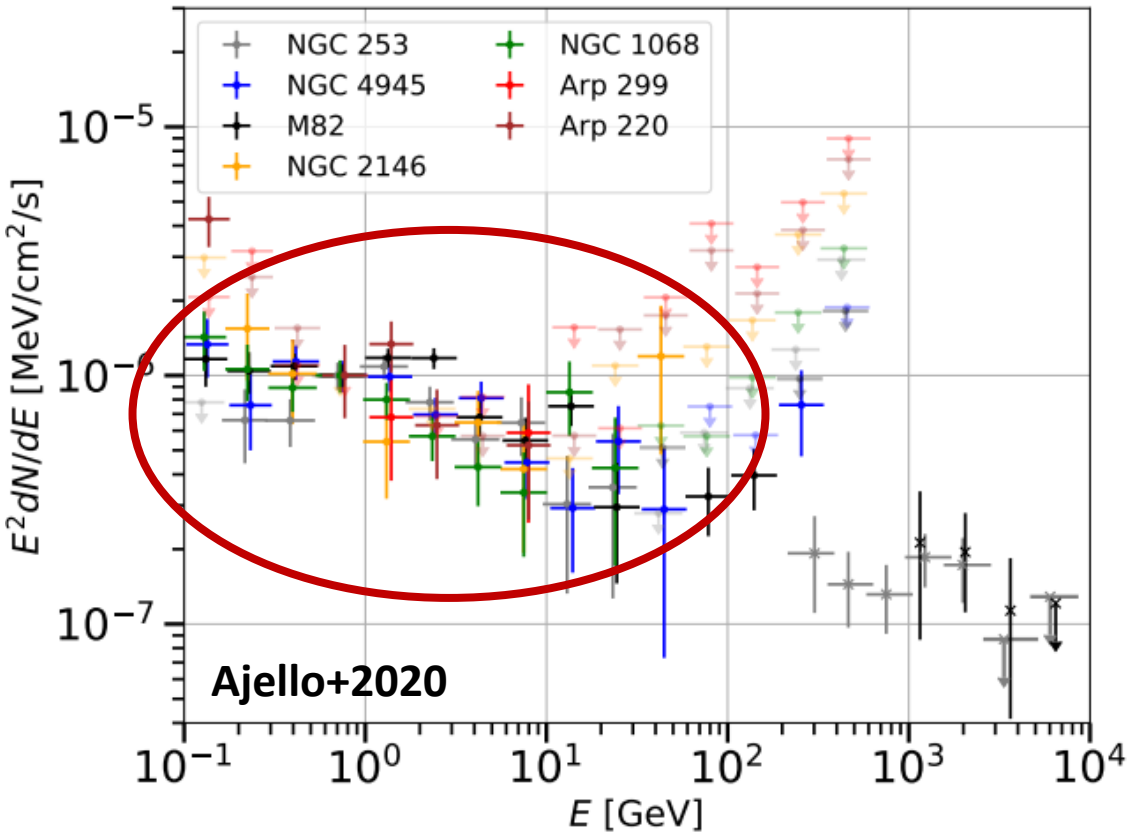

- Starbursts observed at GeV

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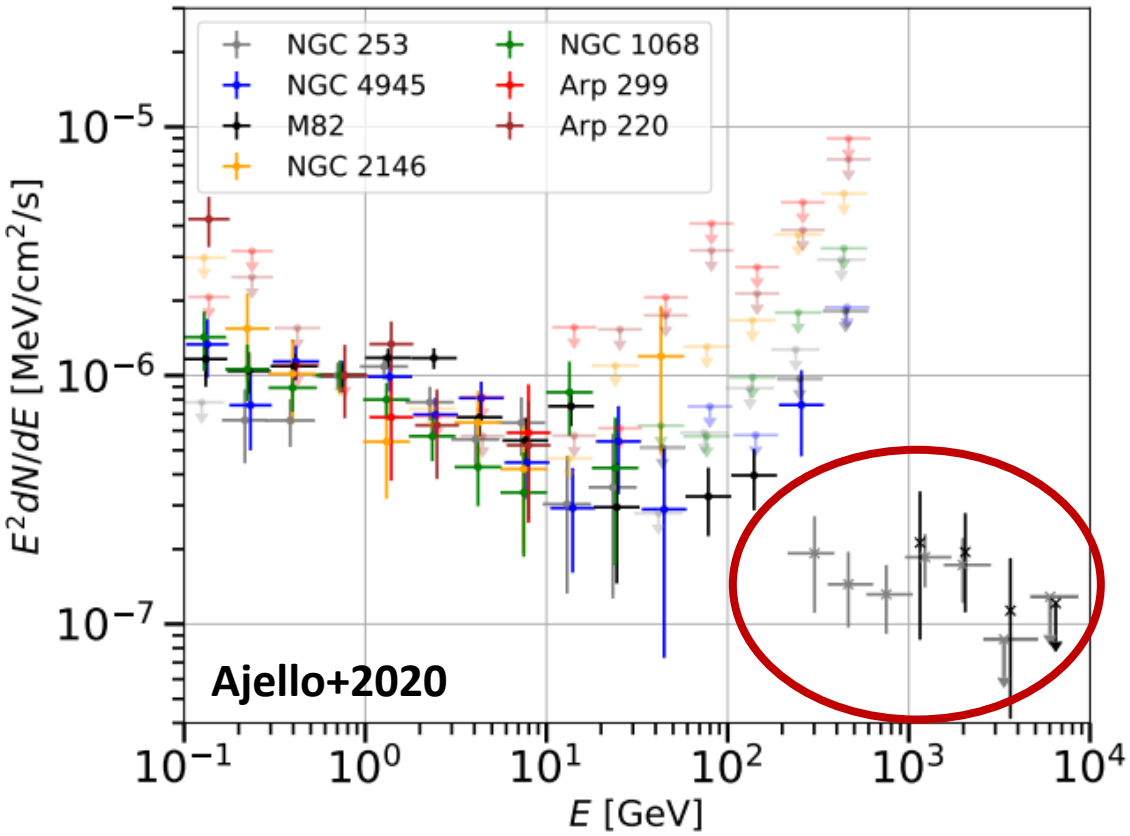
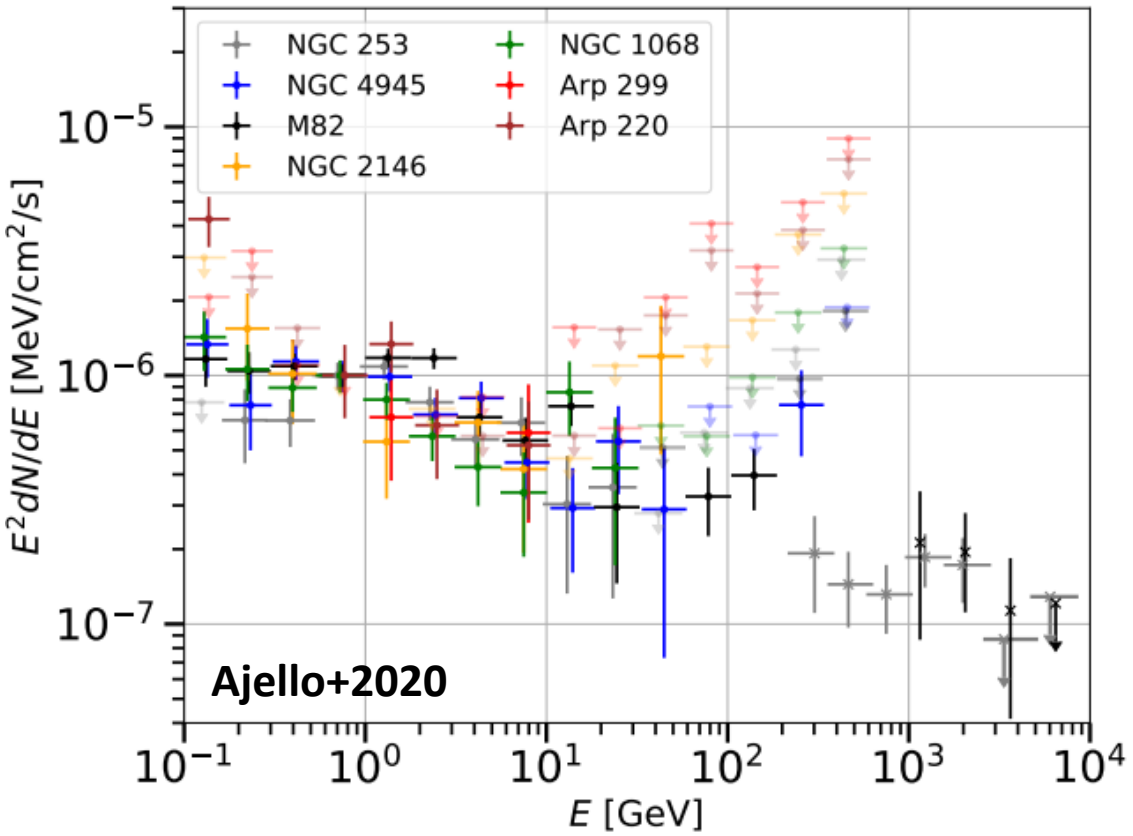


- Starbursts observed at GeV
- Most nearby observed at TeV (<4 Mpc)

Observation of Starburst Galaxies - Gamma



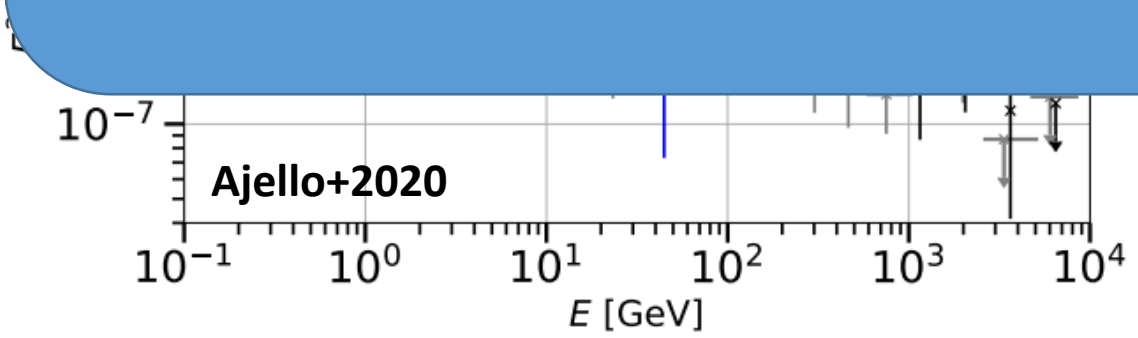
- Starbursts observed at GeV
- Most nearby observed at TeV (<4 Mpc)
- Most distant: Arp 220 (77 Mpc)

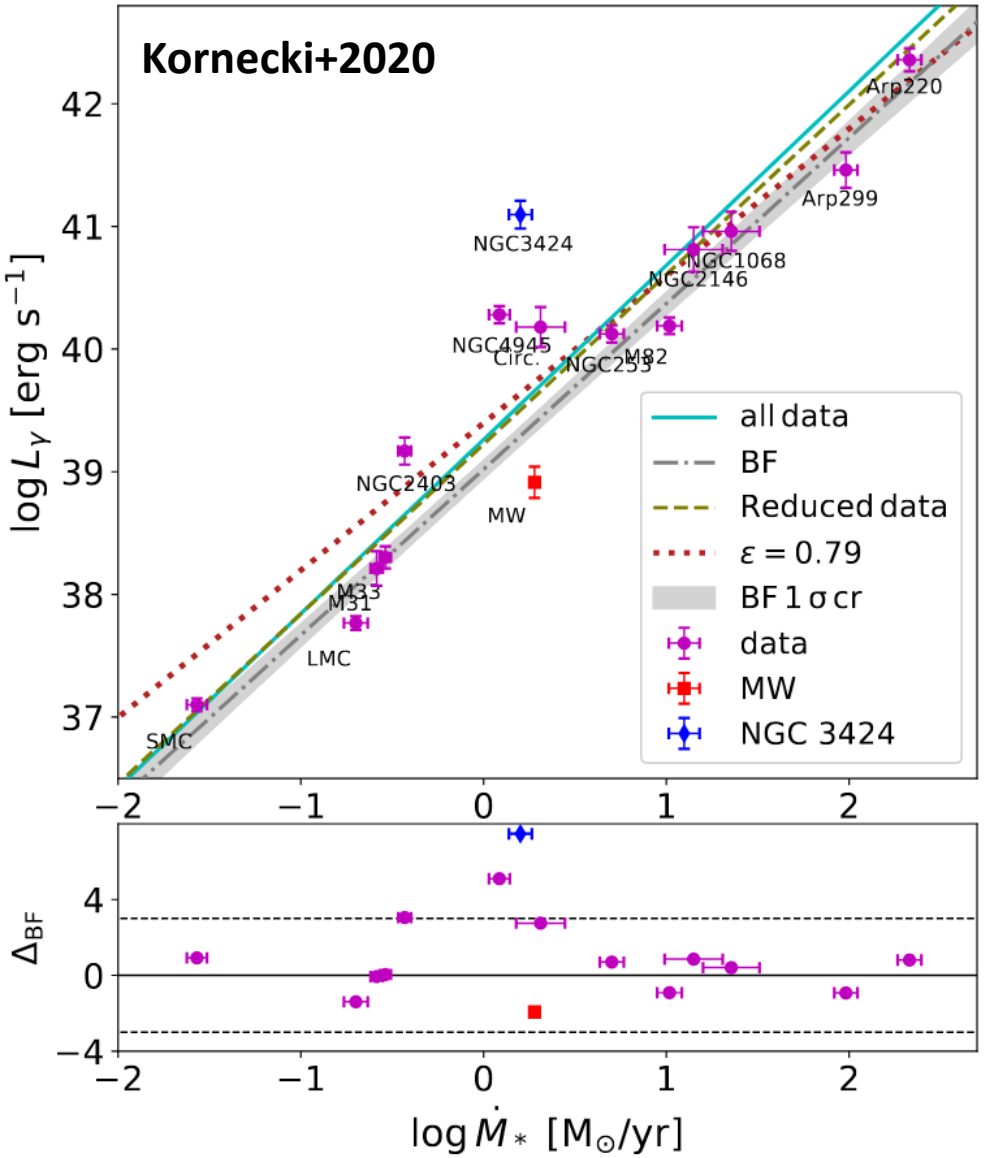
Observation of Starburst Galaxies - Gamma

SFR – gamma-ray correlation

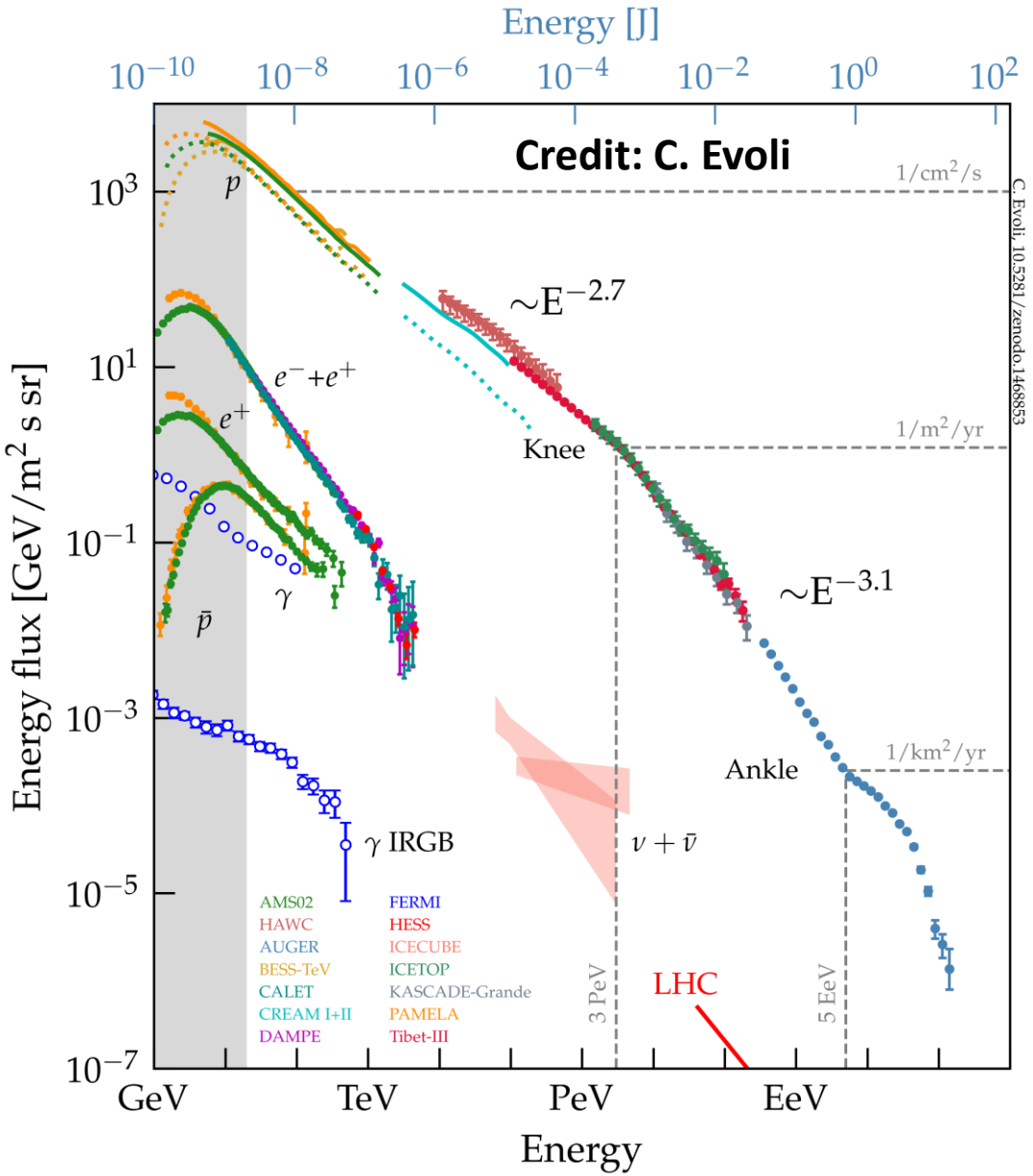
SFR → acceleration sites → CRs

CR interactions → Non-thermal rad.



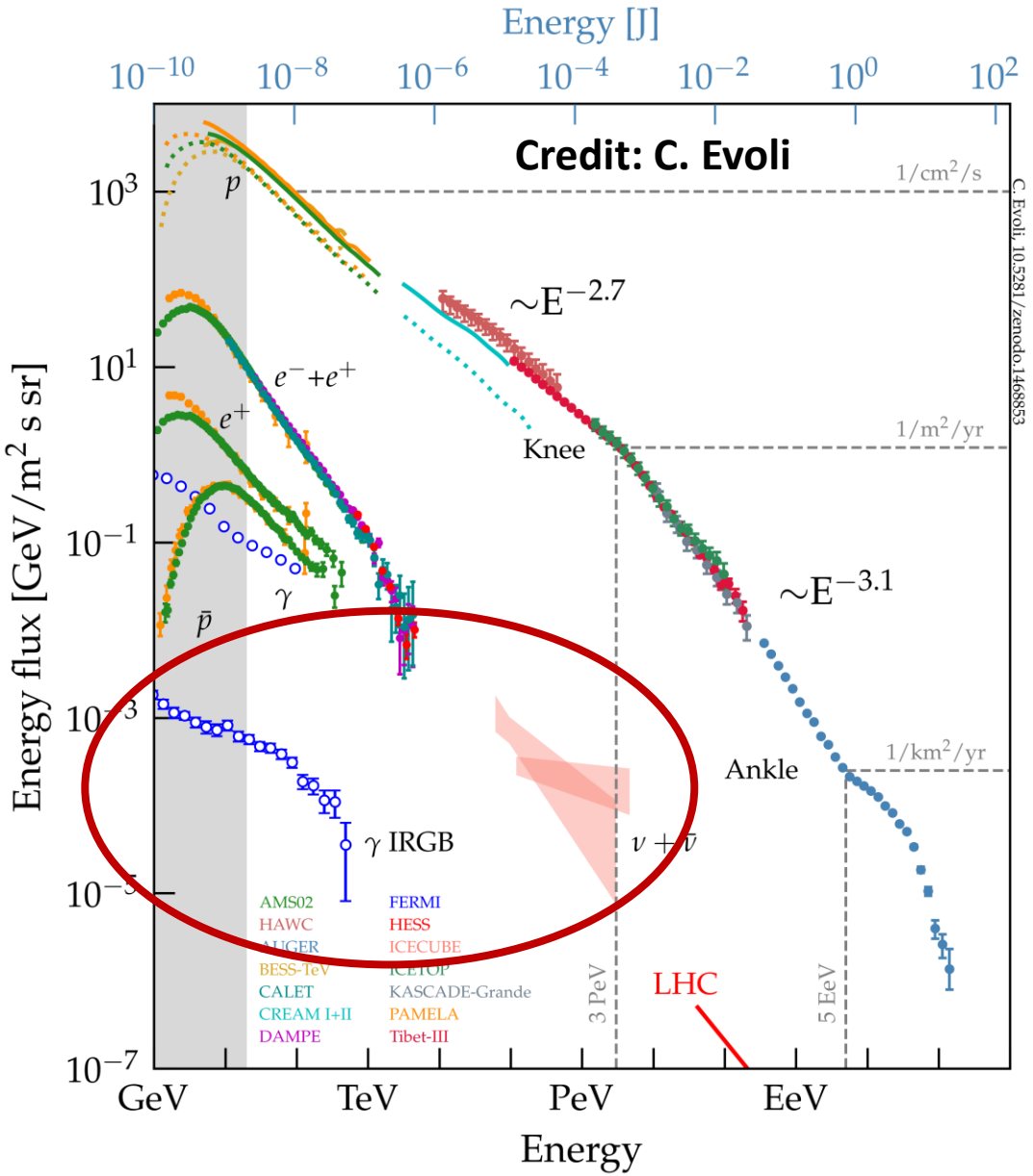


Diffuse radiation from starburst



Starbursts are expected to shine on gamma rays and neutrinos

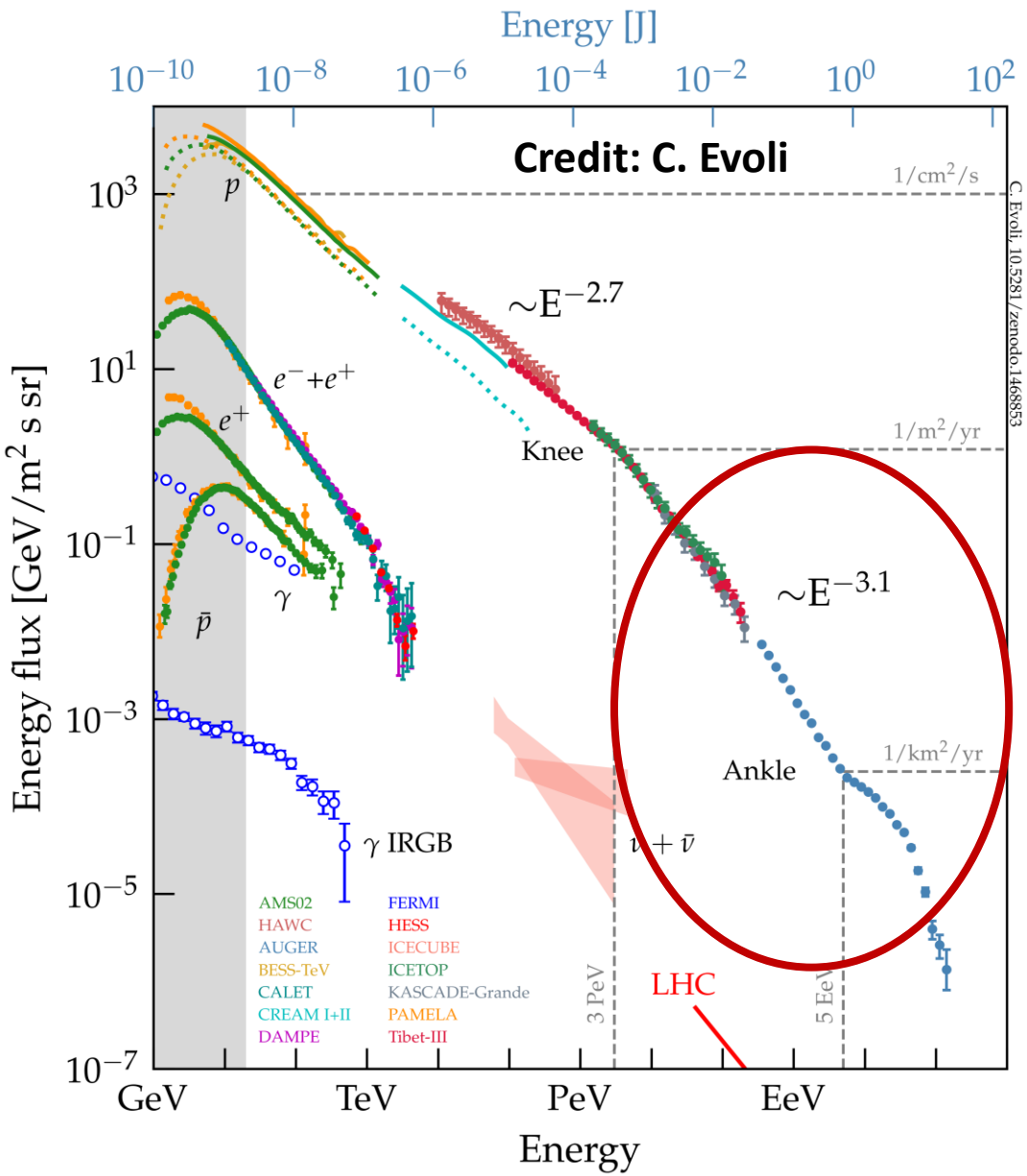
Diffuse radiation from starburst



Starbursts are expected to shine on gamma rays and neutrinos

- At which level can they contribute to the observed diffuse fluxes?

Diffuse radiation from starburst

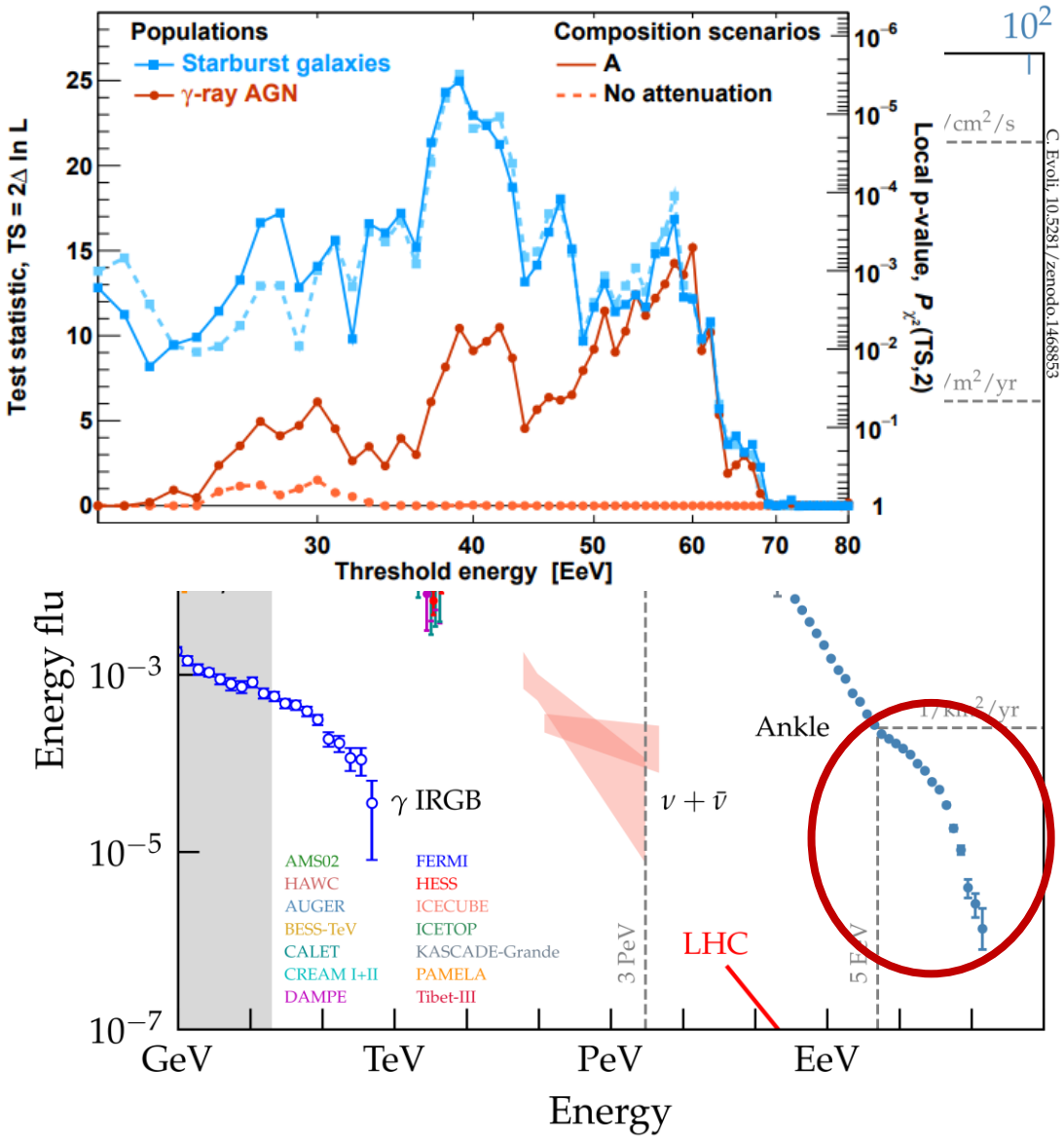


Starbursts are expected to shine on gamma rays and neutrinos

- At which level can they contribute to the observed diffuse fluxes?
- Can they contribute to the CR flux at some level?

Diffuse radiation from starburst

Aab+2018 - PAO



Starbursts are expected to shine on gamma rays and neutrinos

- At which level can they contribute to the observed diffuse fluxes?
- Can they contribute to the CR flux at some level?
- SBGs and UHECRs?

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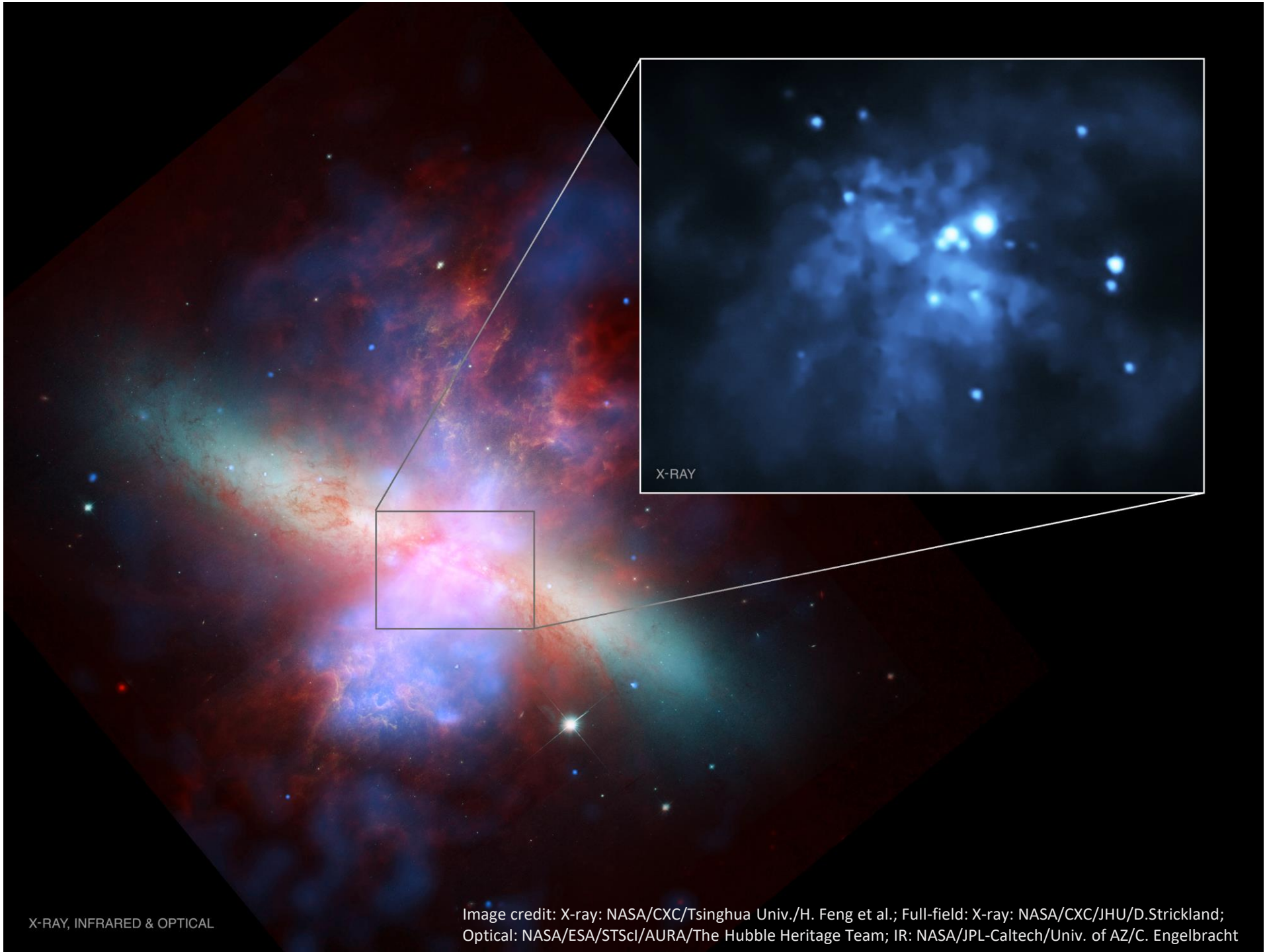
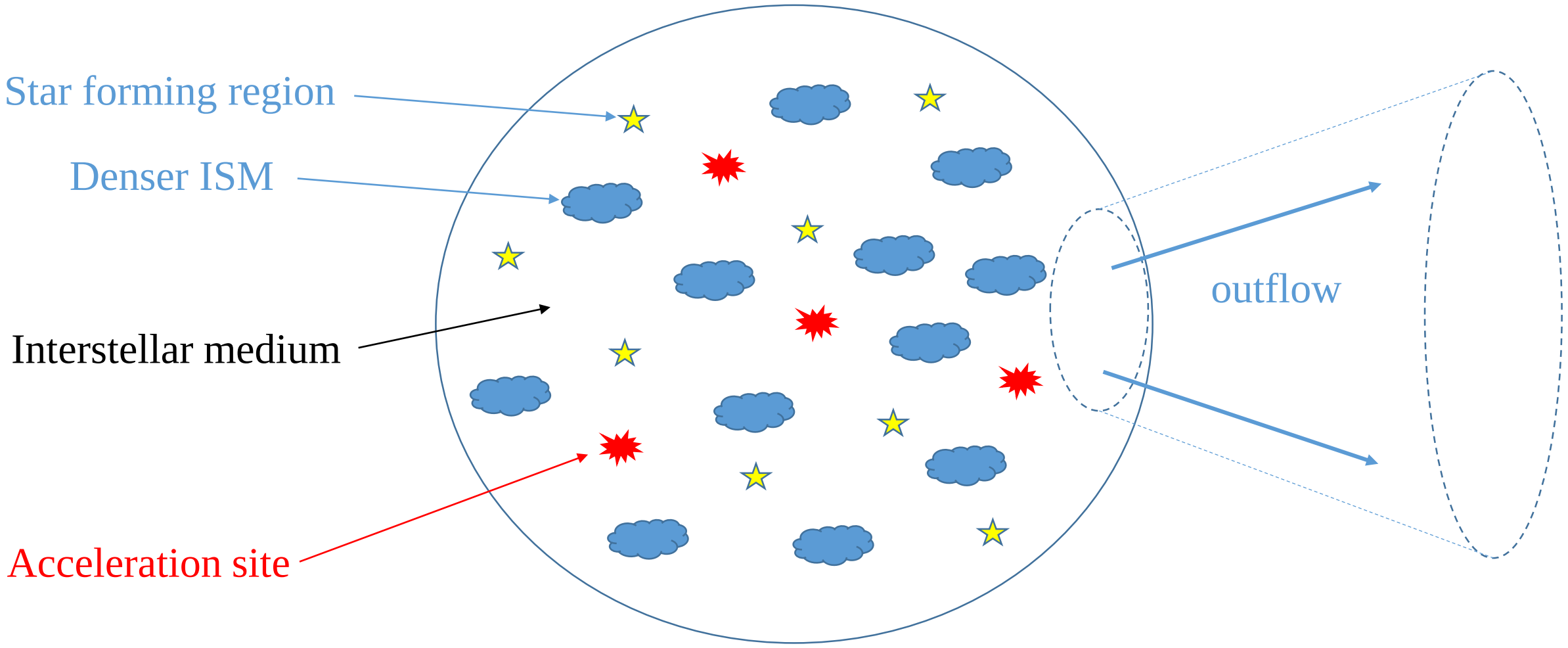


Image credit: X-ray: NASA/CXC/Tsinghua Univ./H. Feng et al.; Full-field: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht

Particle transport in starburst nuclei



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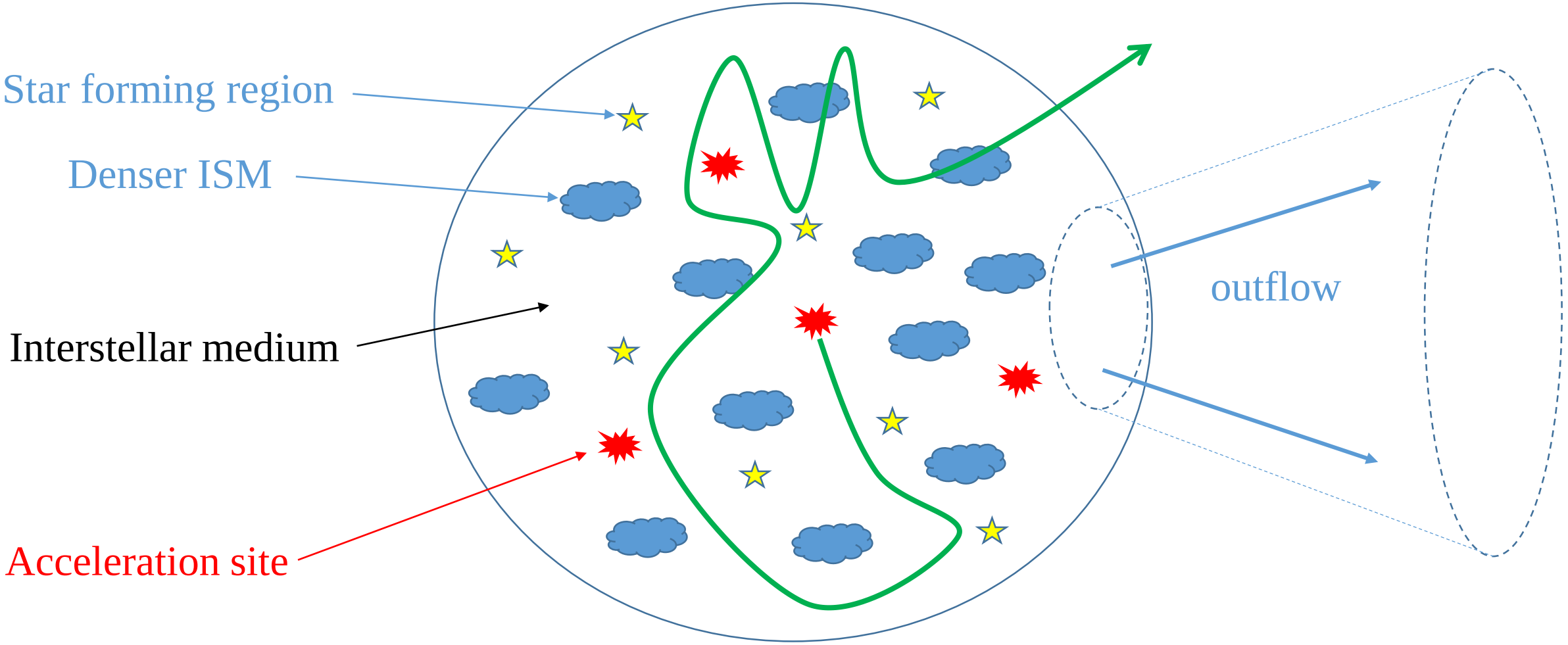

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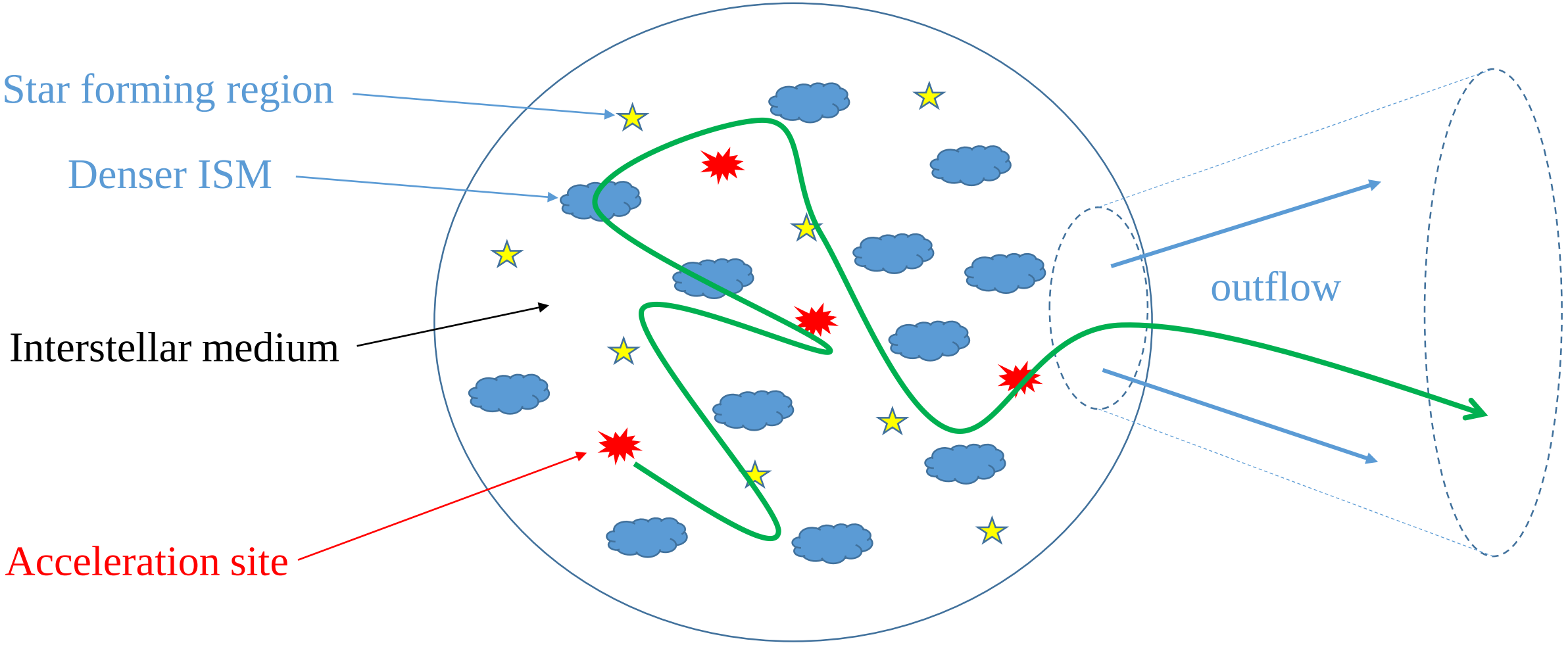

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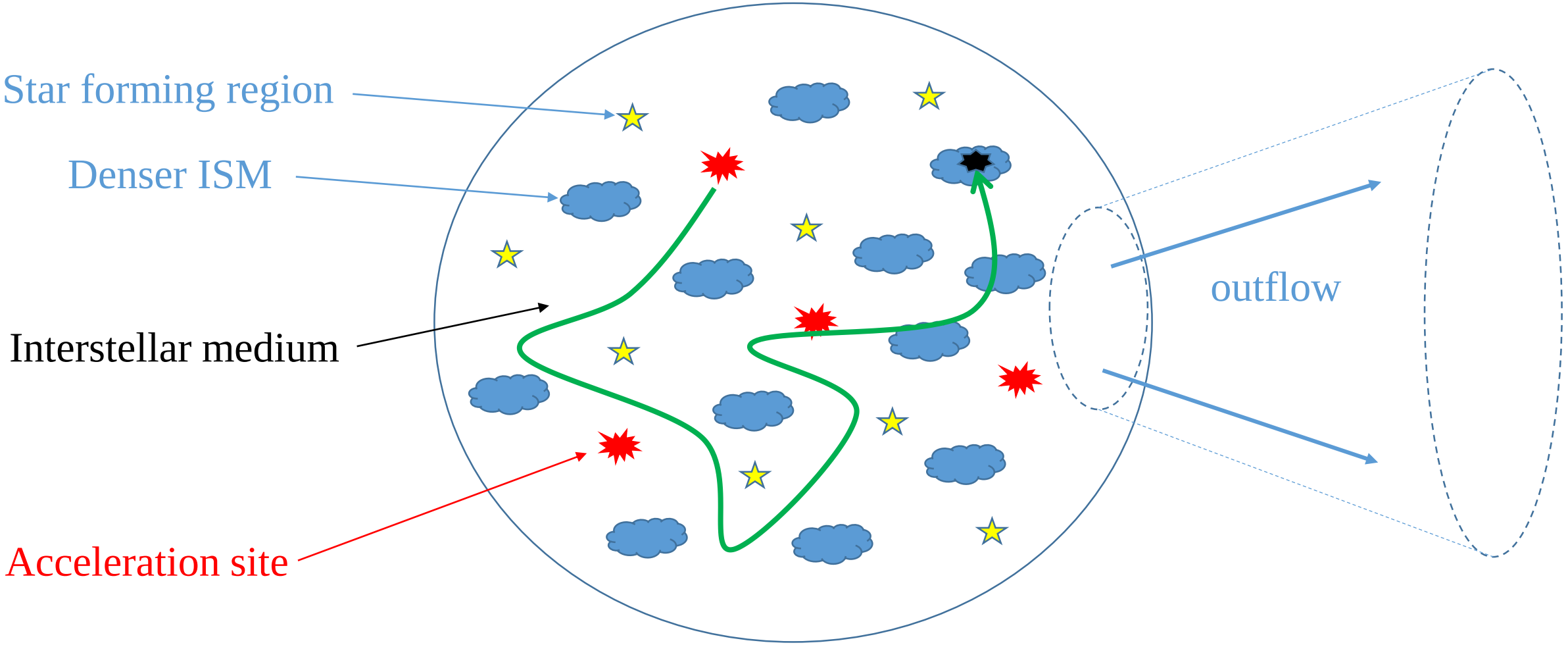
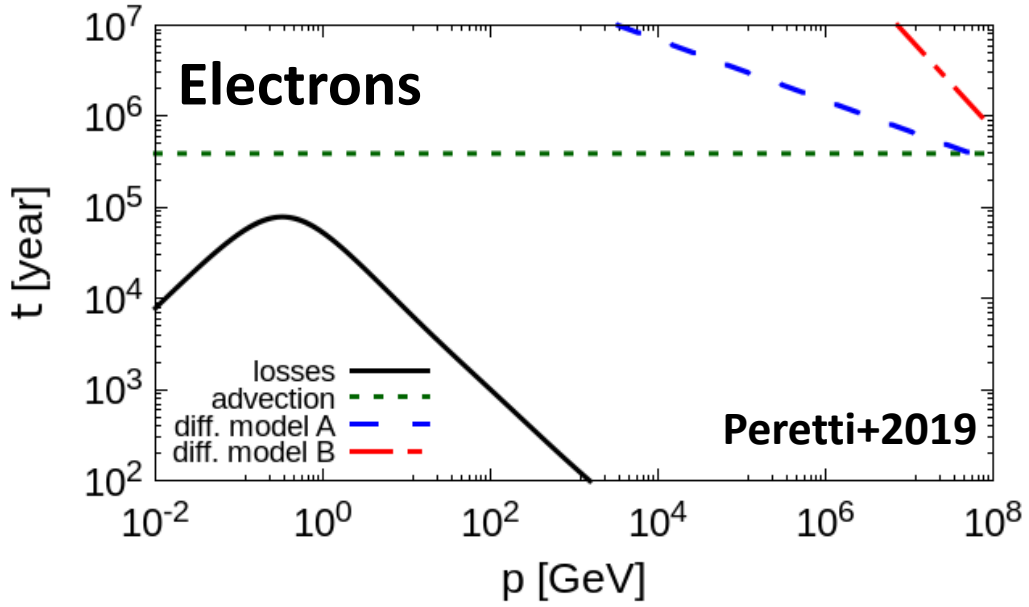
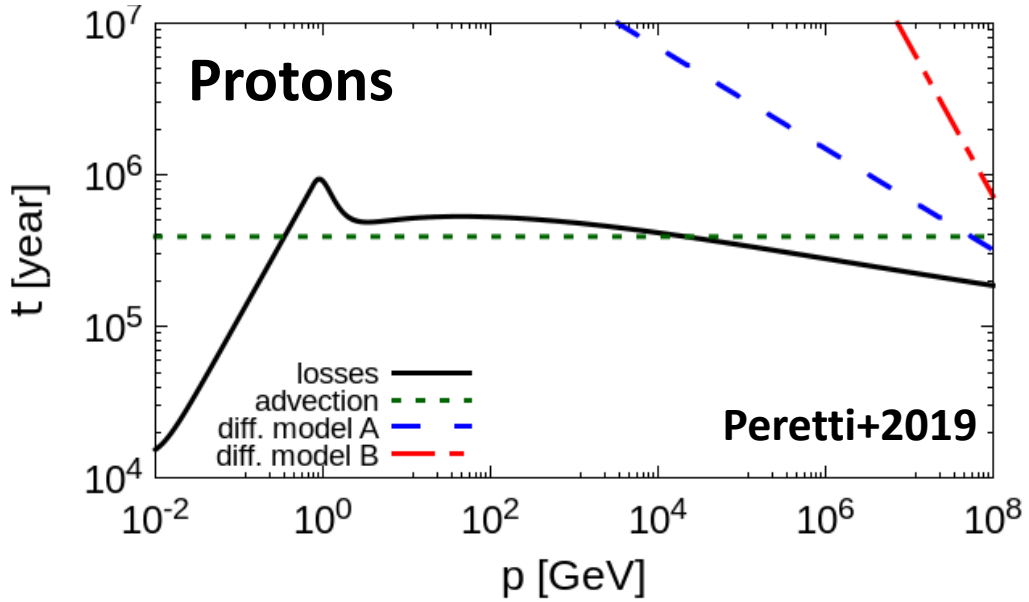


Modeling the transport in SBNi





$$n \approx 10^2\ cm^{-3}$$

$$B \approx 10^2\ \mu G$$

$$U_{RAD} \approx 10^3\ eV\ cm^{-3}$$

$$v \approx 10^2\ km\ s^{-1}$$

$$D(p) \approx \frac{c}{3}\, r_L^{2-\delta}\, l_c^{\delta-1}$$

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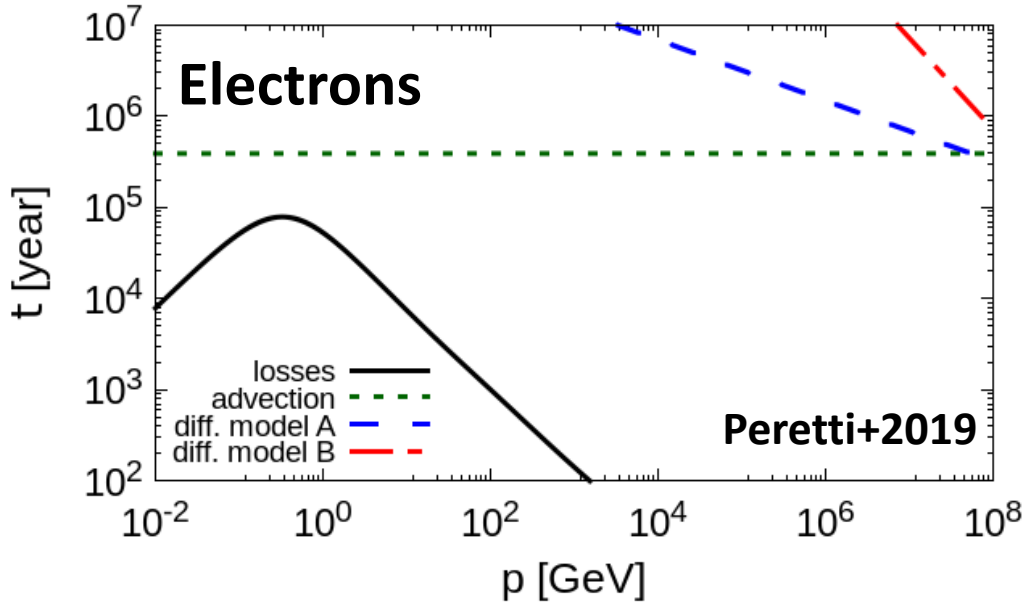
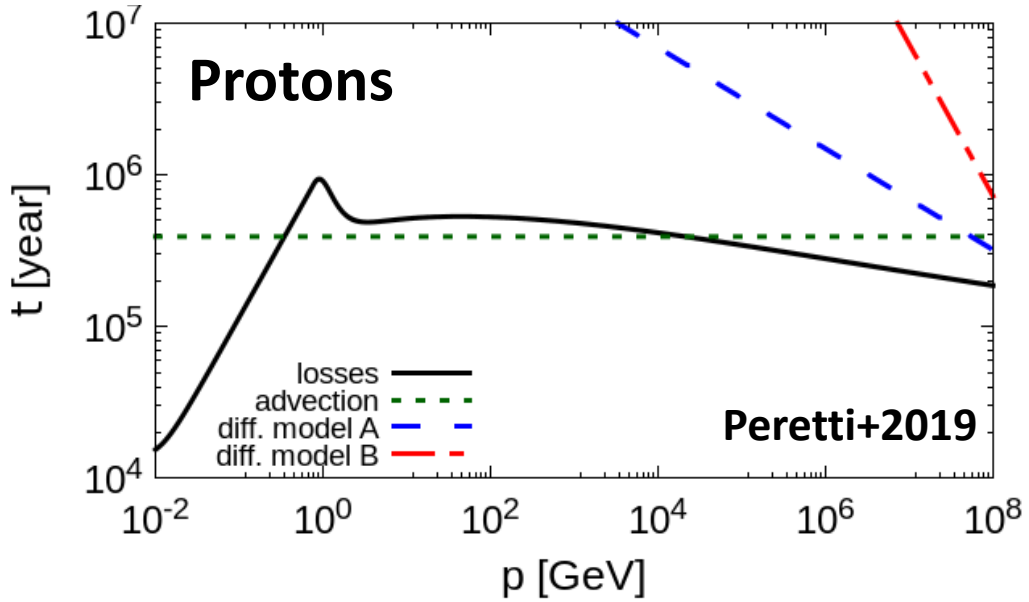
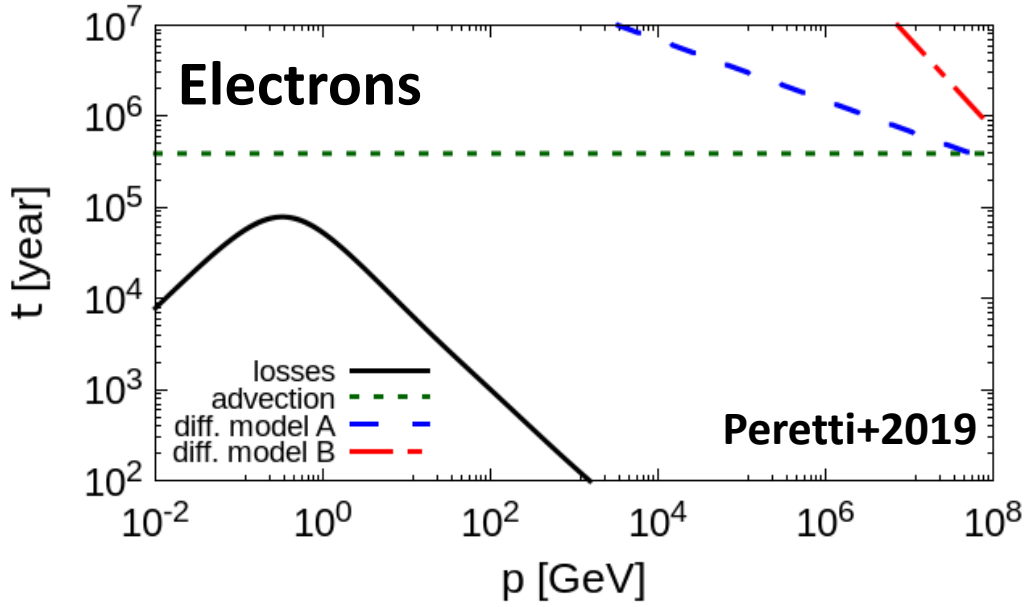
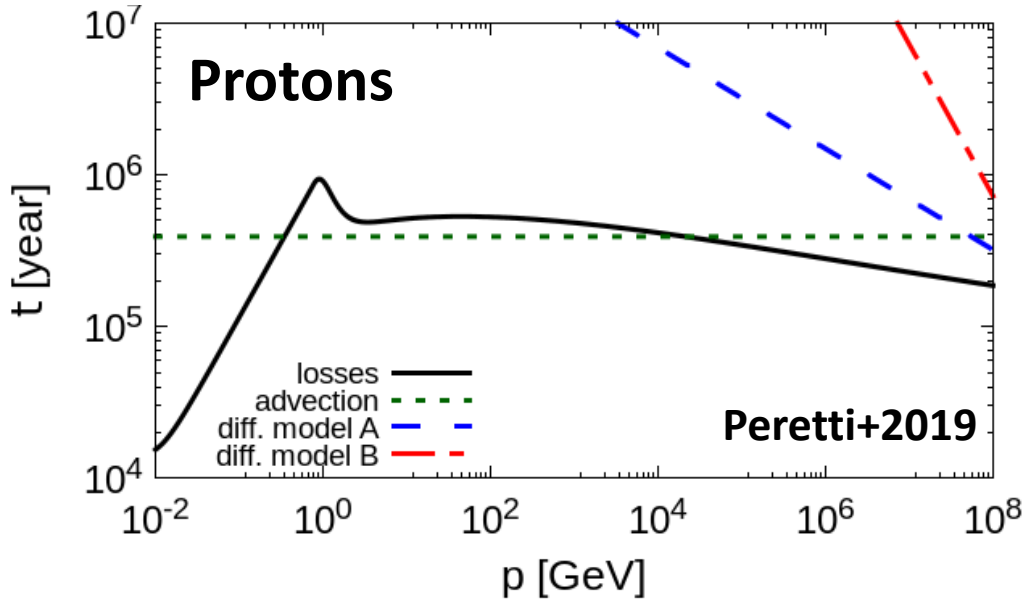




- Electrons are confined in SBNi

Modeling the transport in SBNi





- Electrons are confined in SBNi
- Advection and losses regulate the transport of protons

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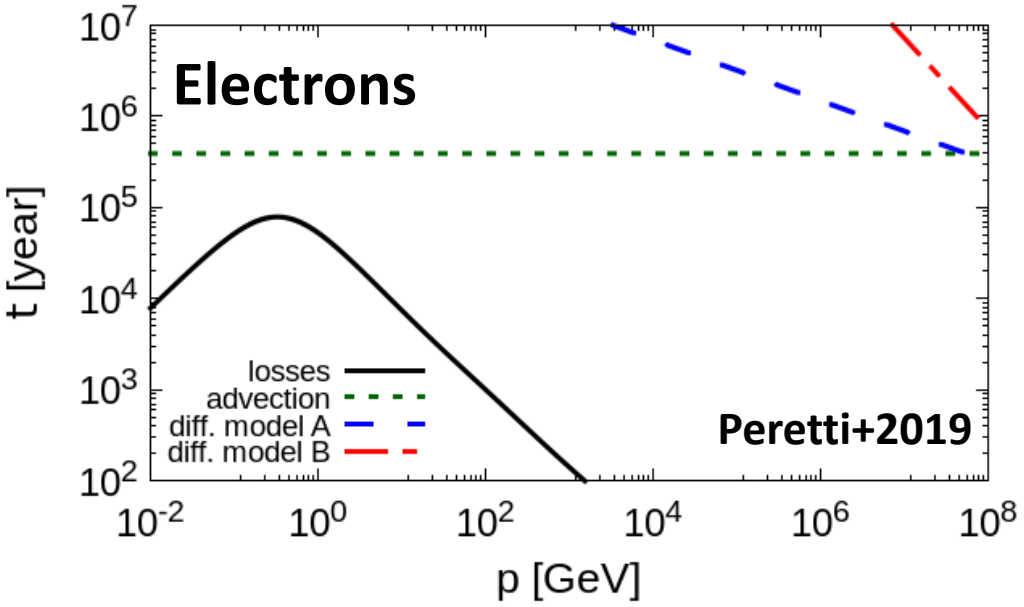
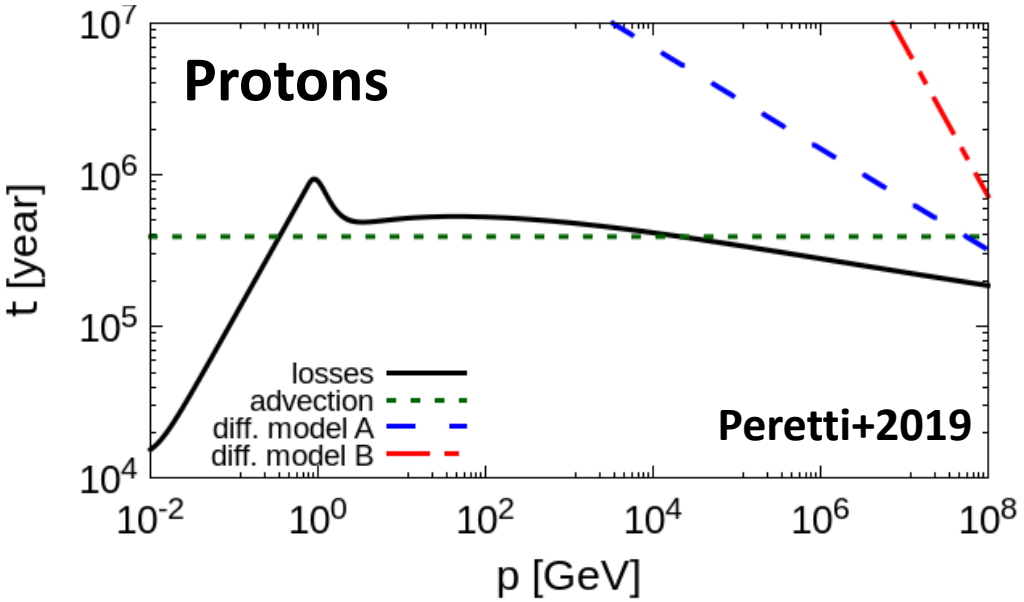
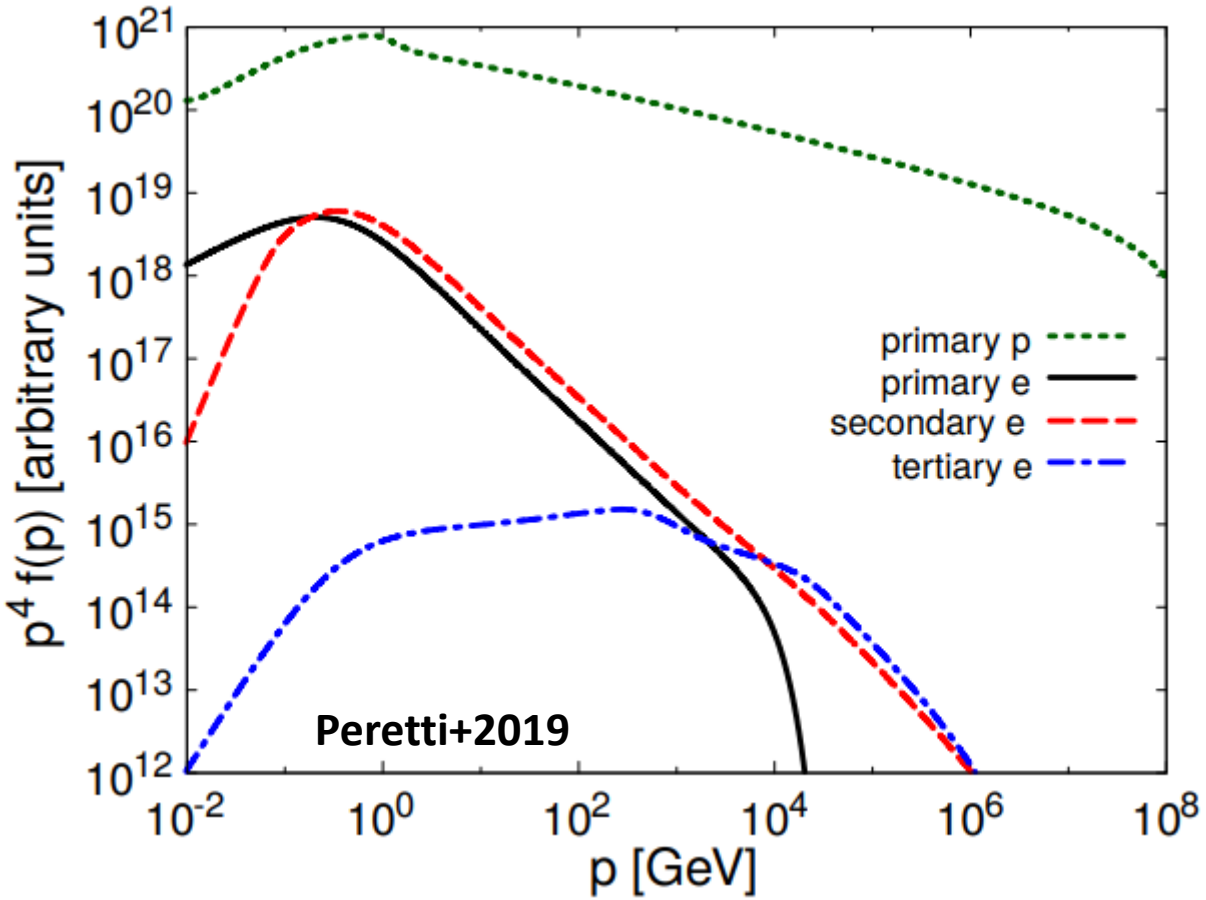


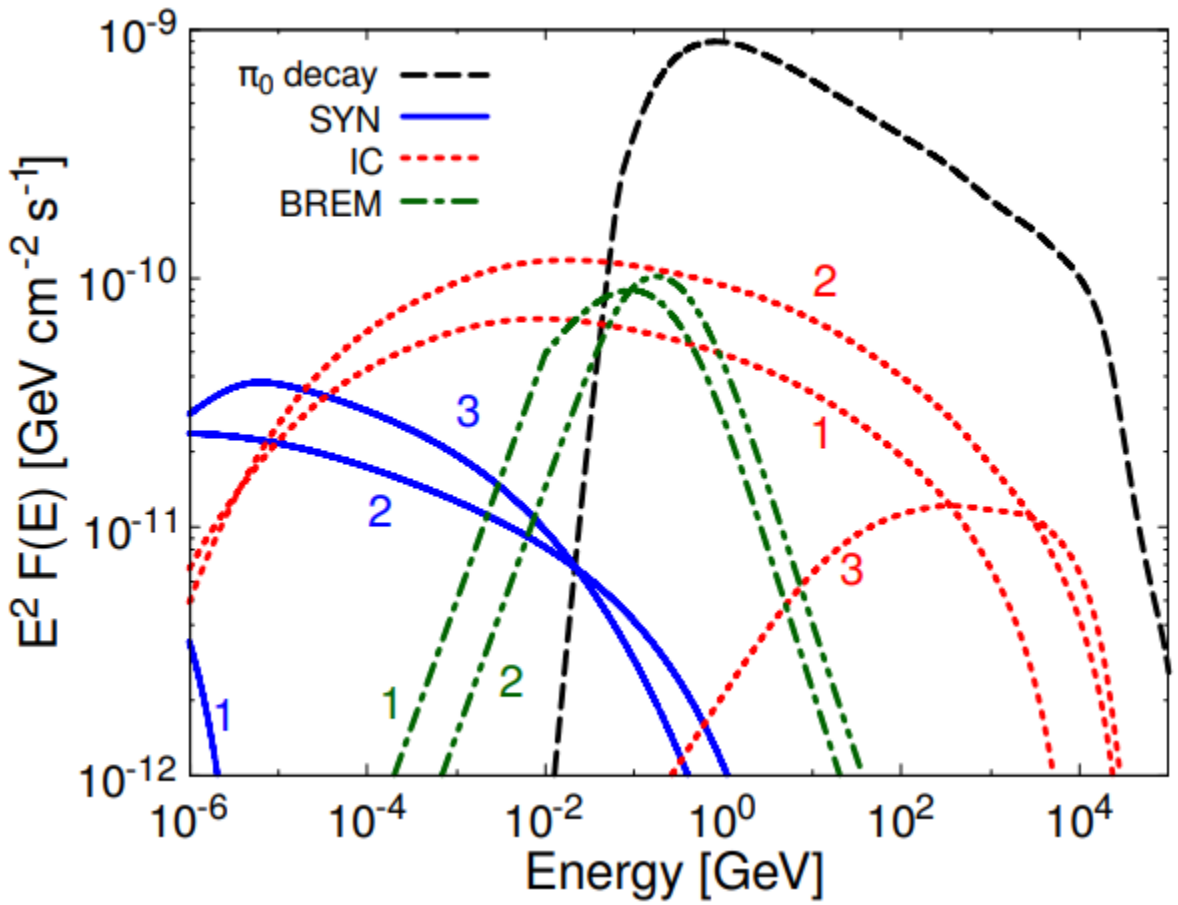


- Electrons are confined in SBNi
- Advection and losses regulate the transport of protons
- Particles experience all phases of the ISM

$$Q = \frac{f}{\tau_{loss}} + \frac{f}{\tau_{diff}} + \frac{f}{\tau_{adv}}$$

Particle and photon spectra in SBNi





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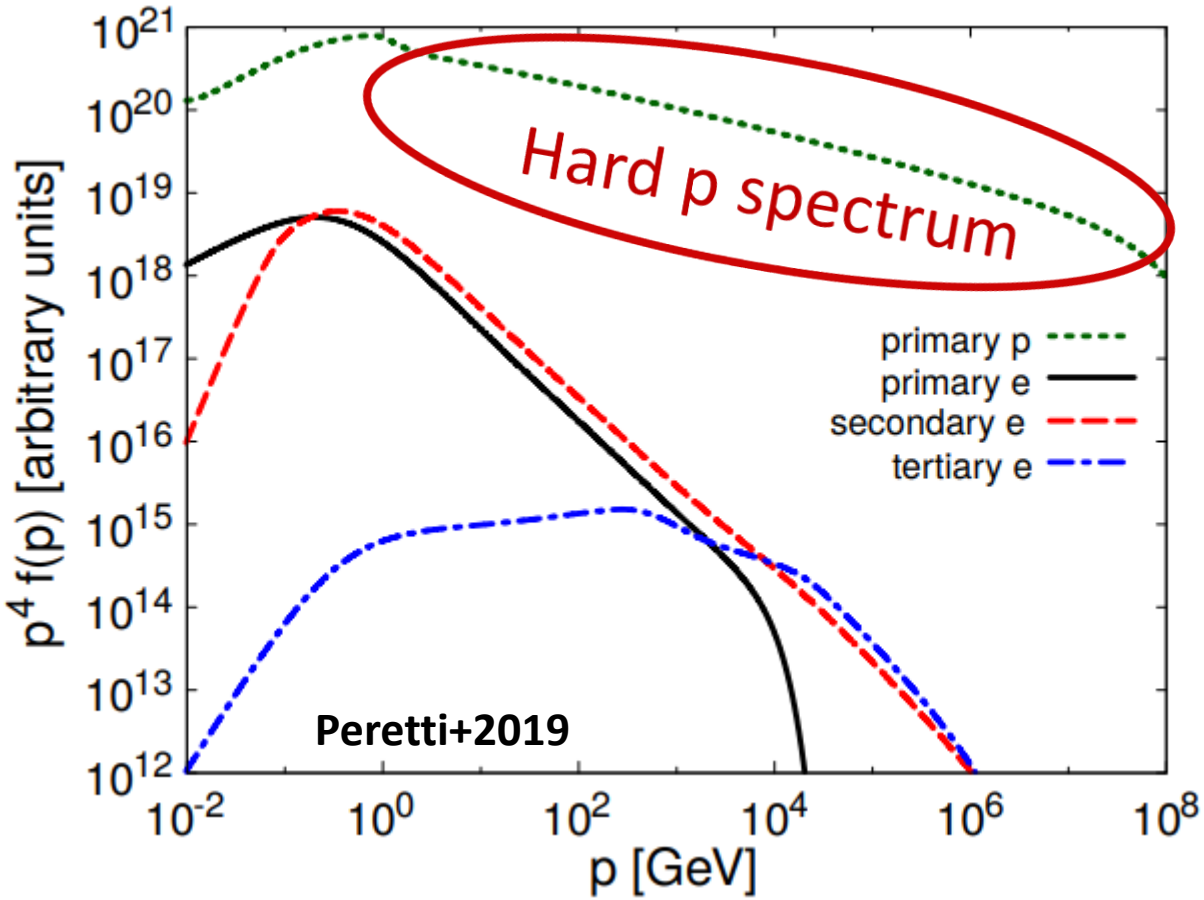

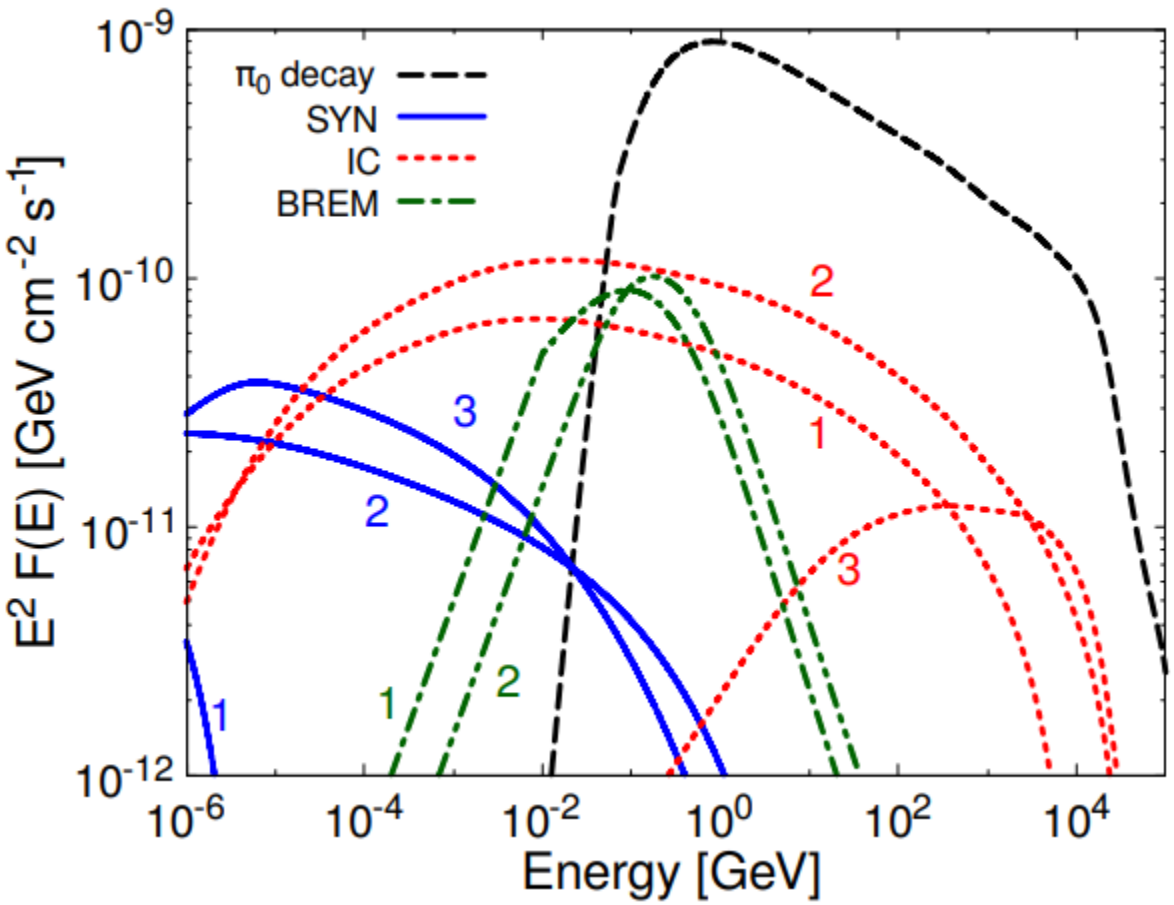

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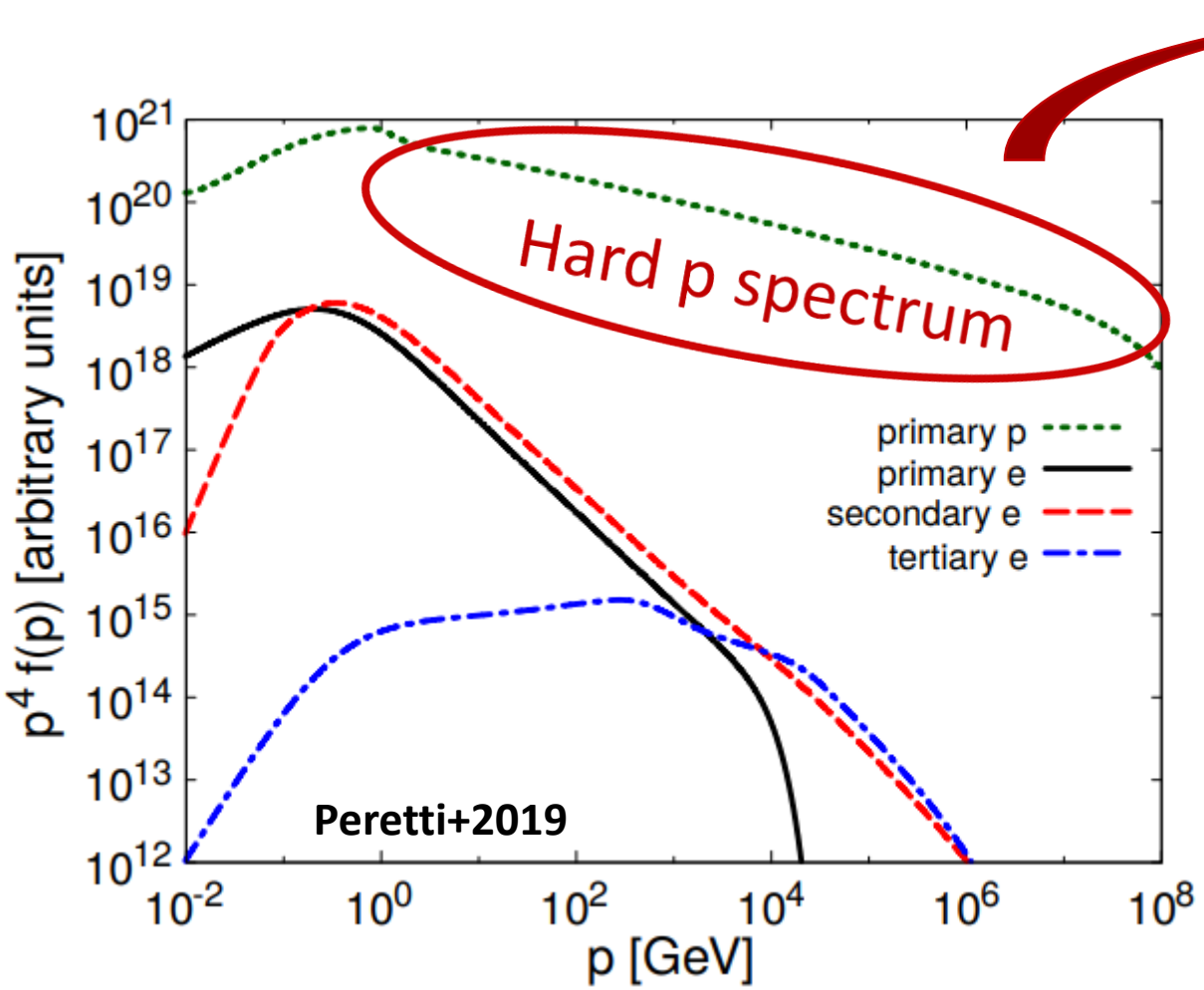

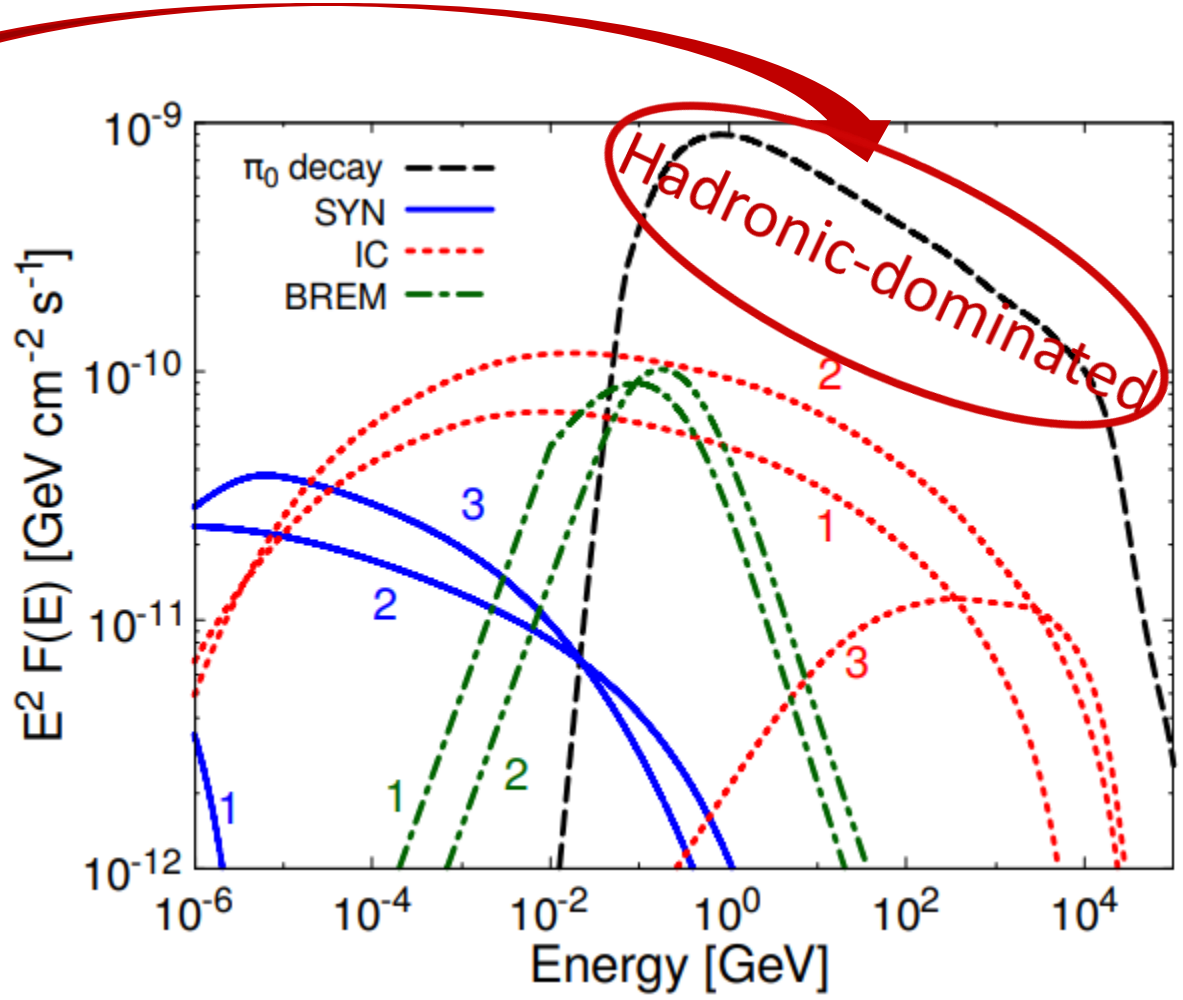

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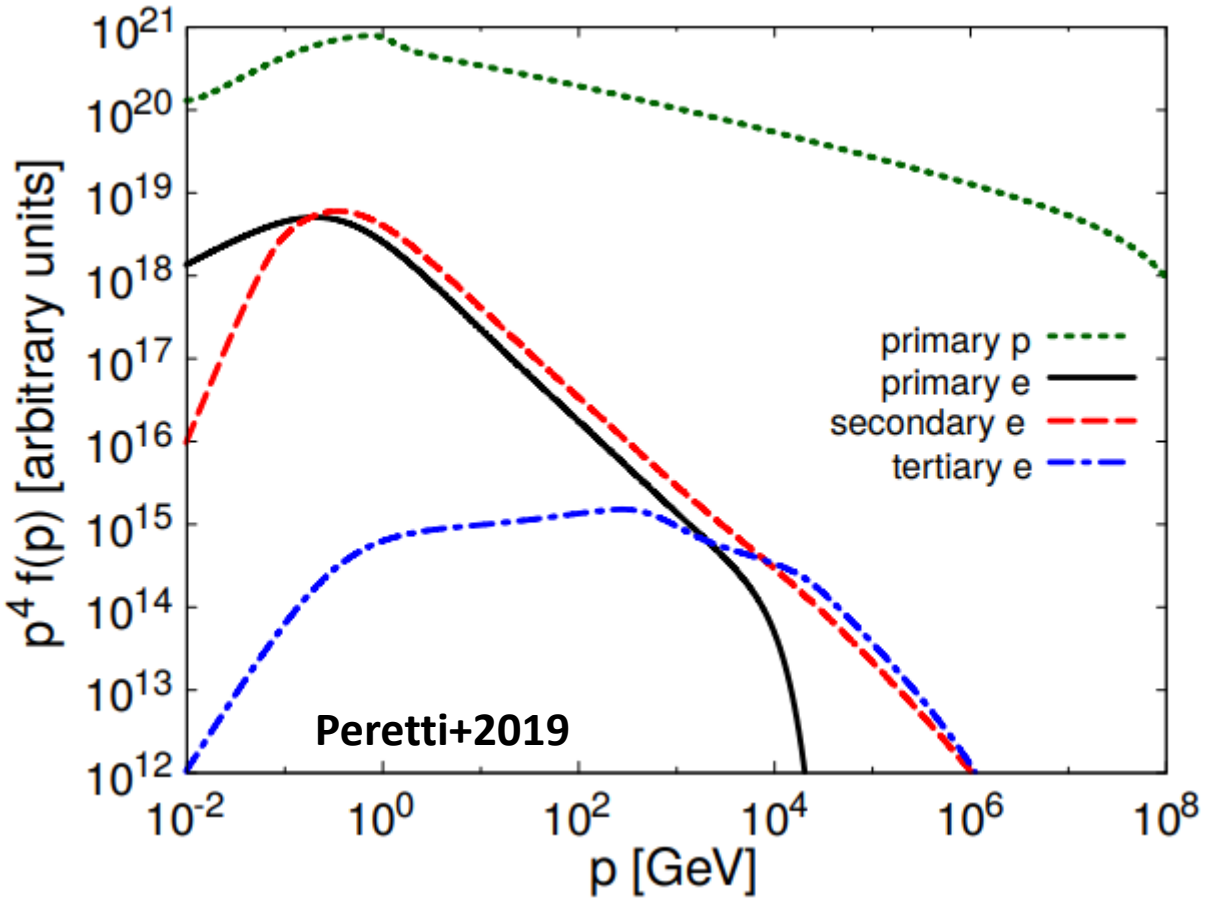
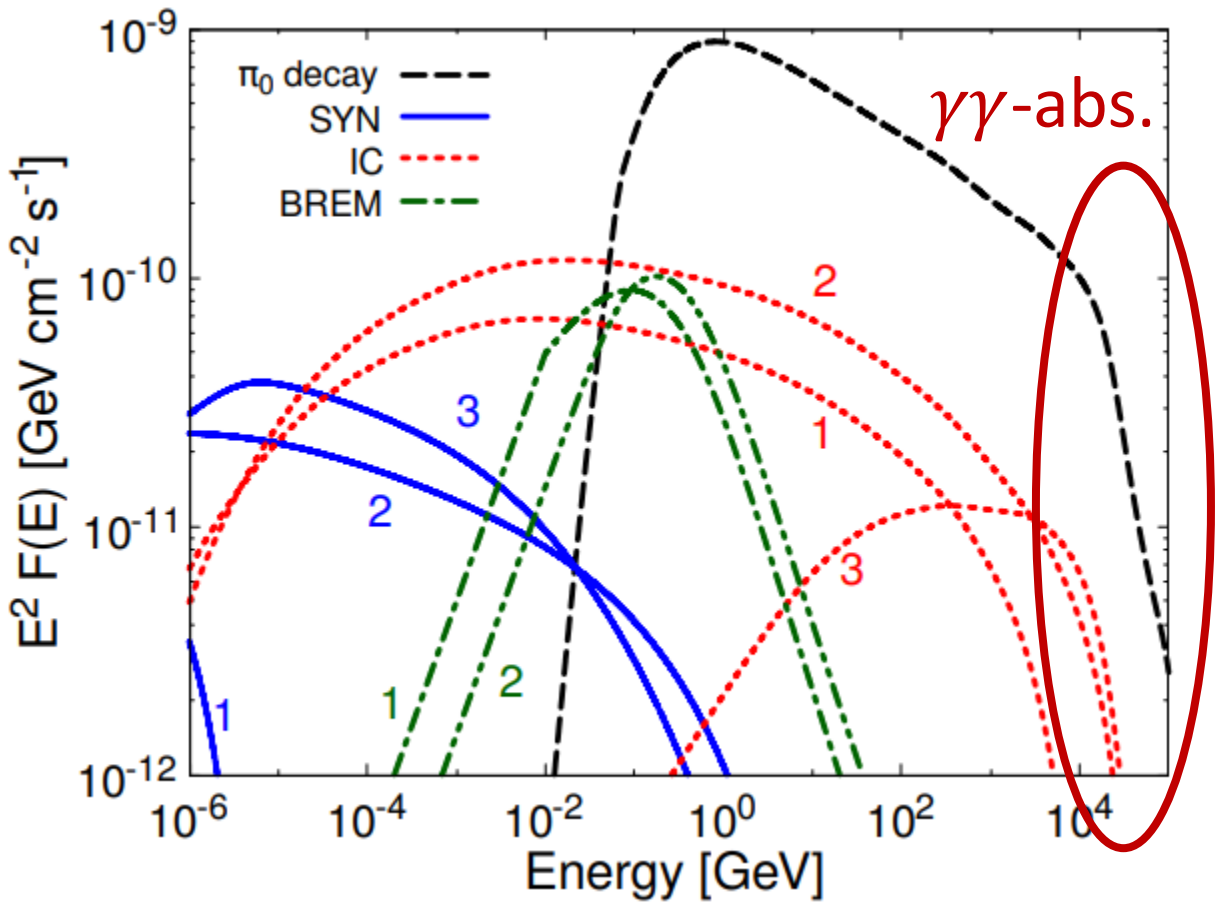
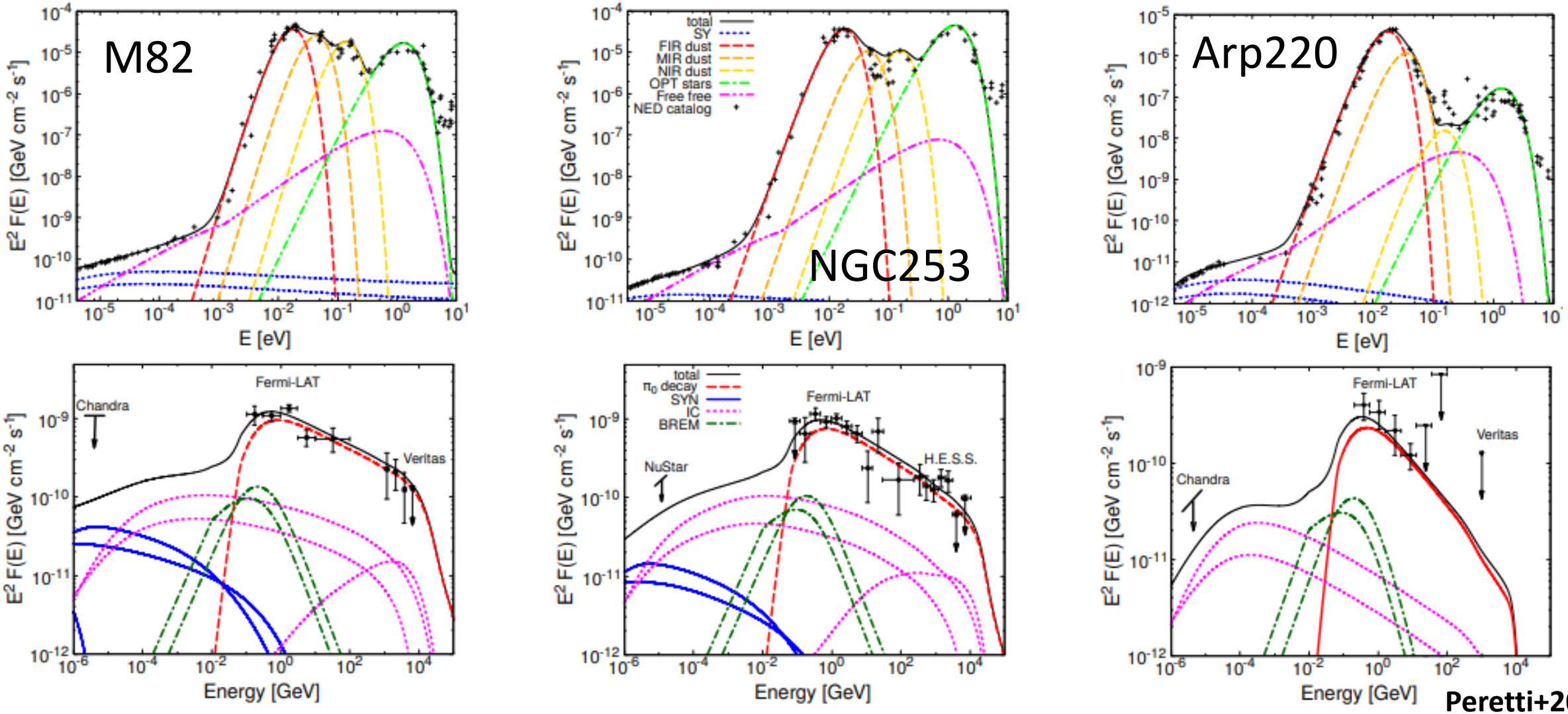




Modeling nearby SBGs



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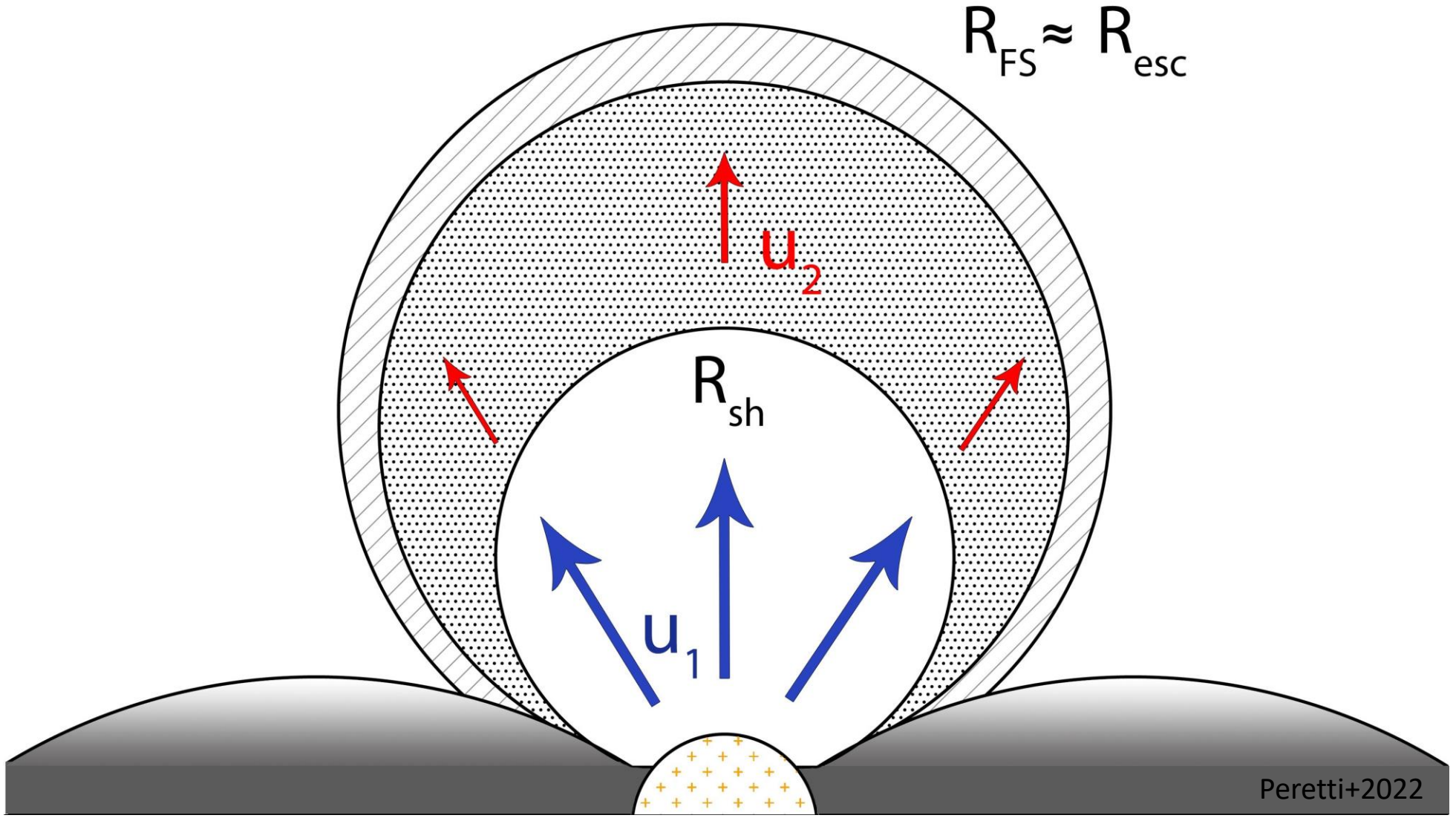
Acceleration and transport in starburst winds



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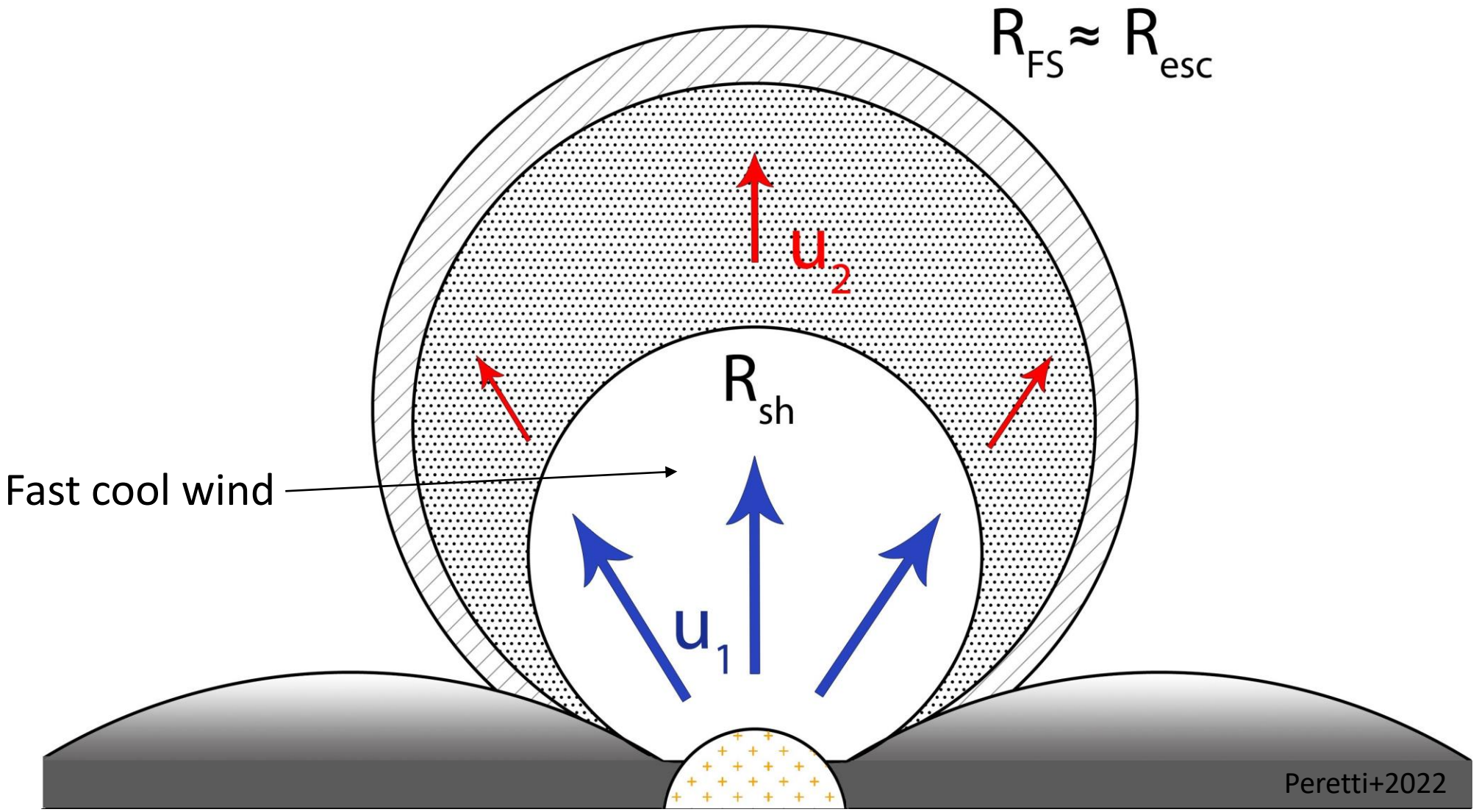

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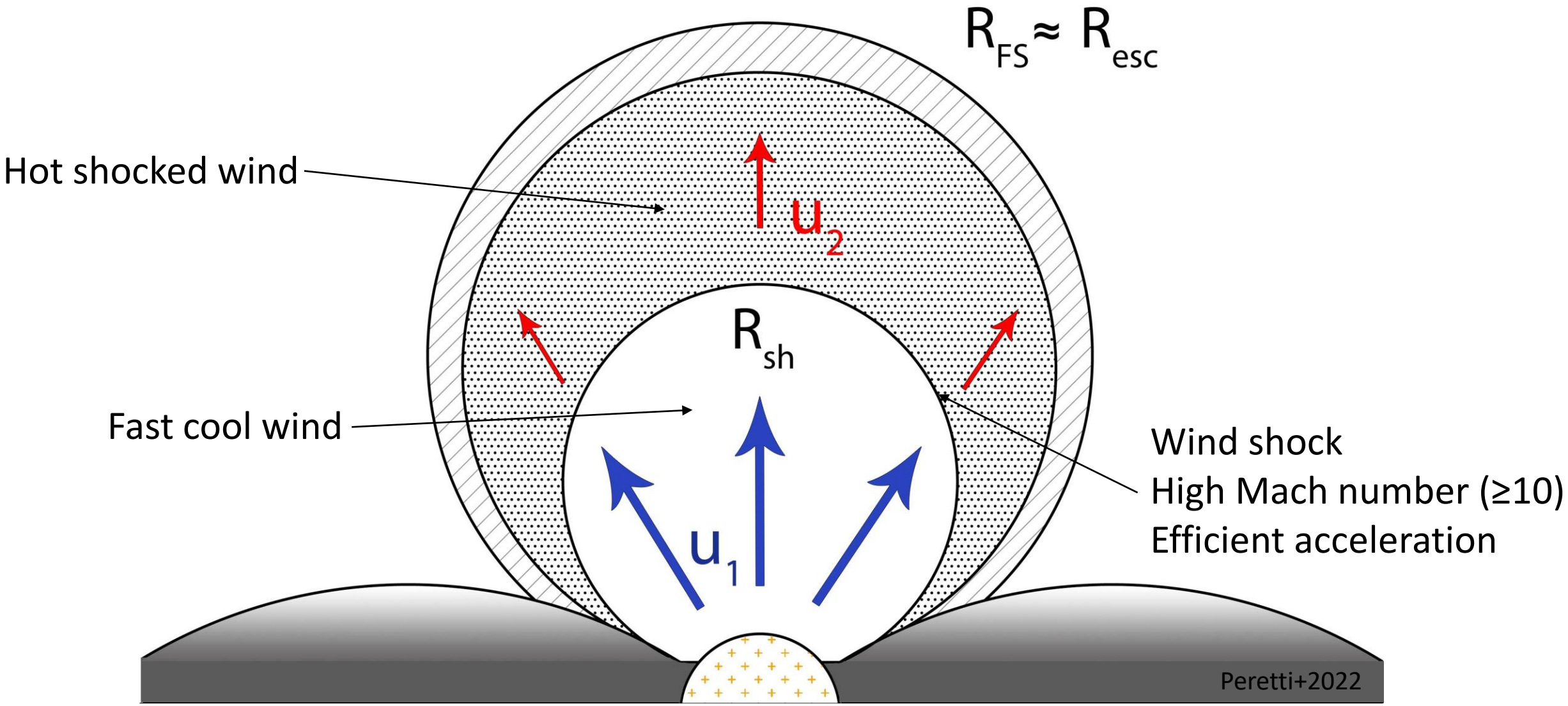

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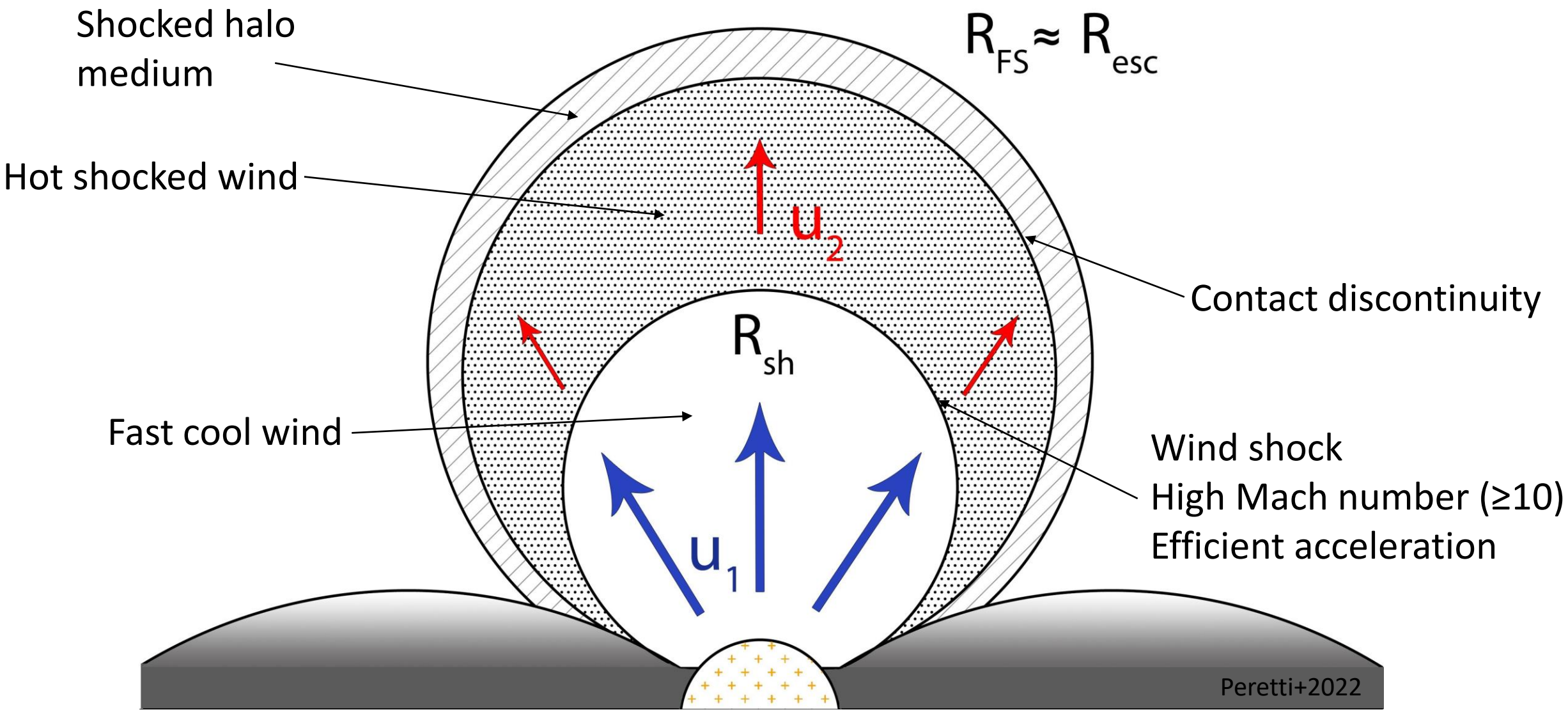

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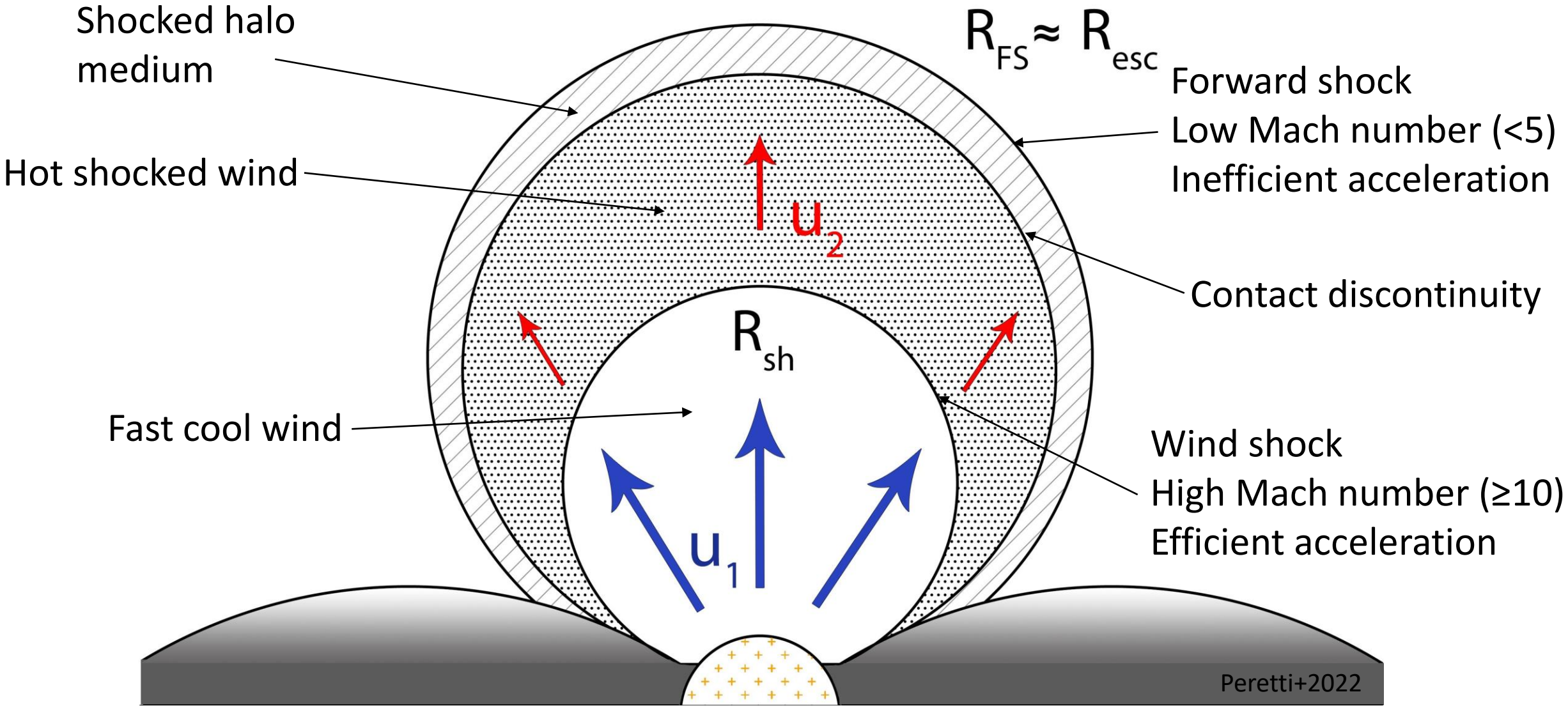

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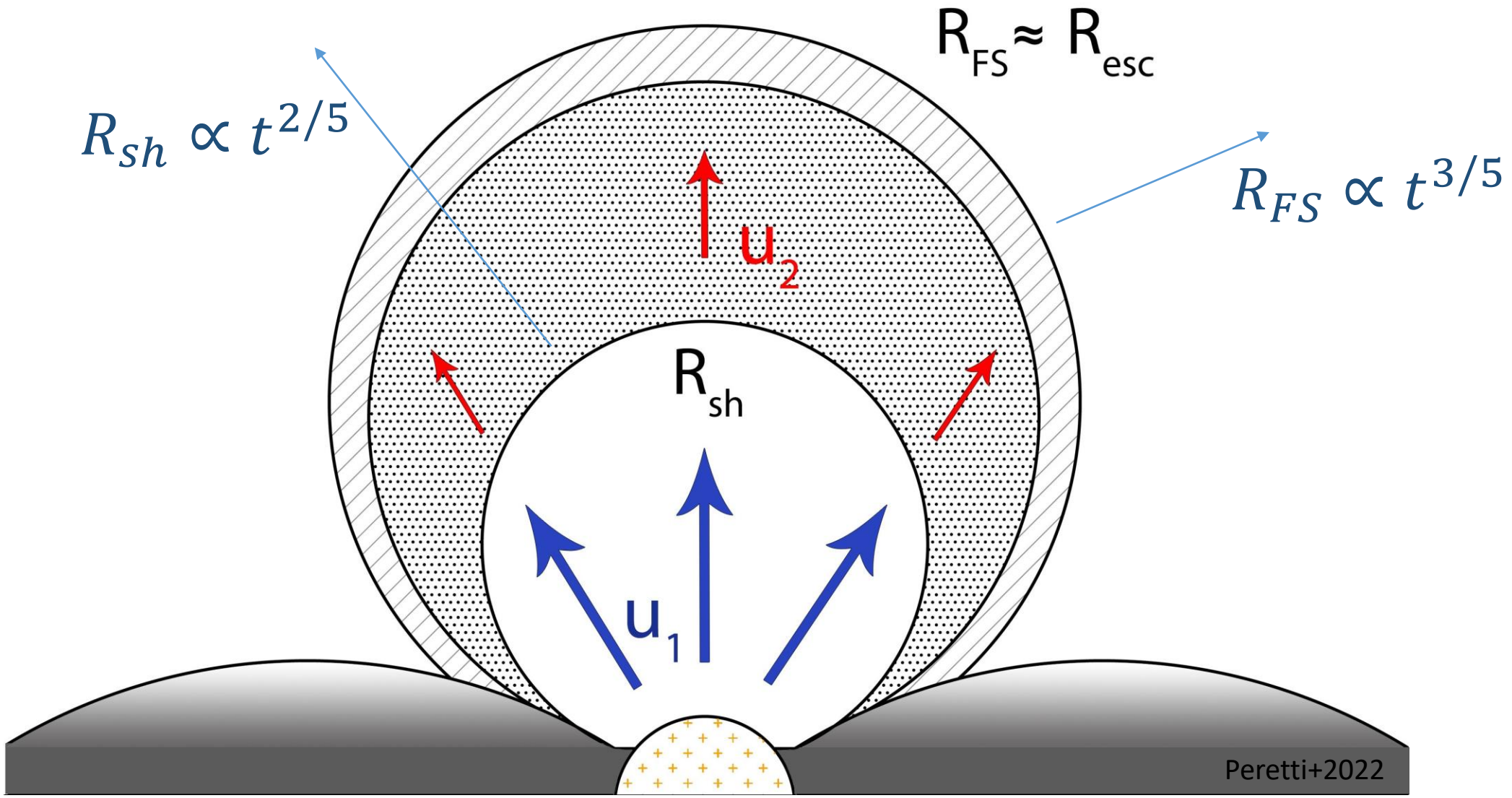
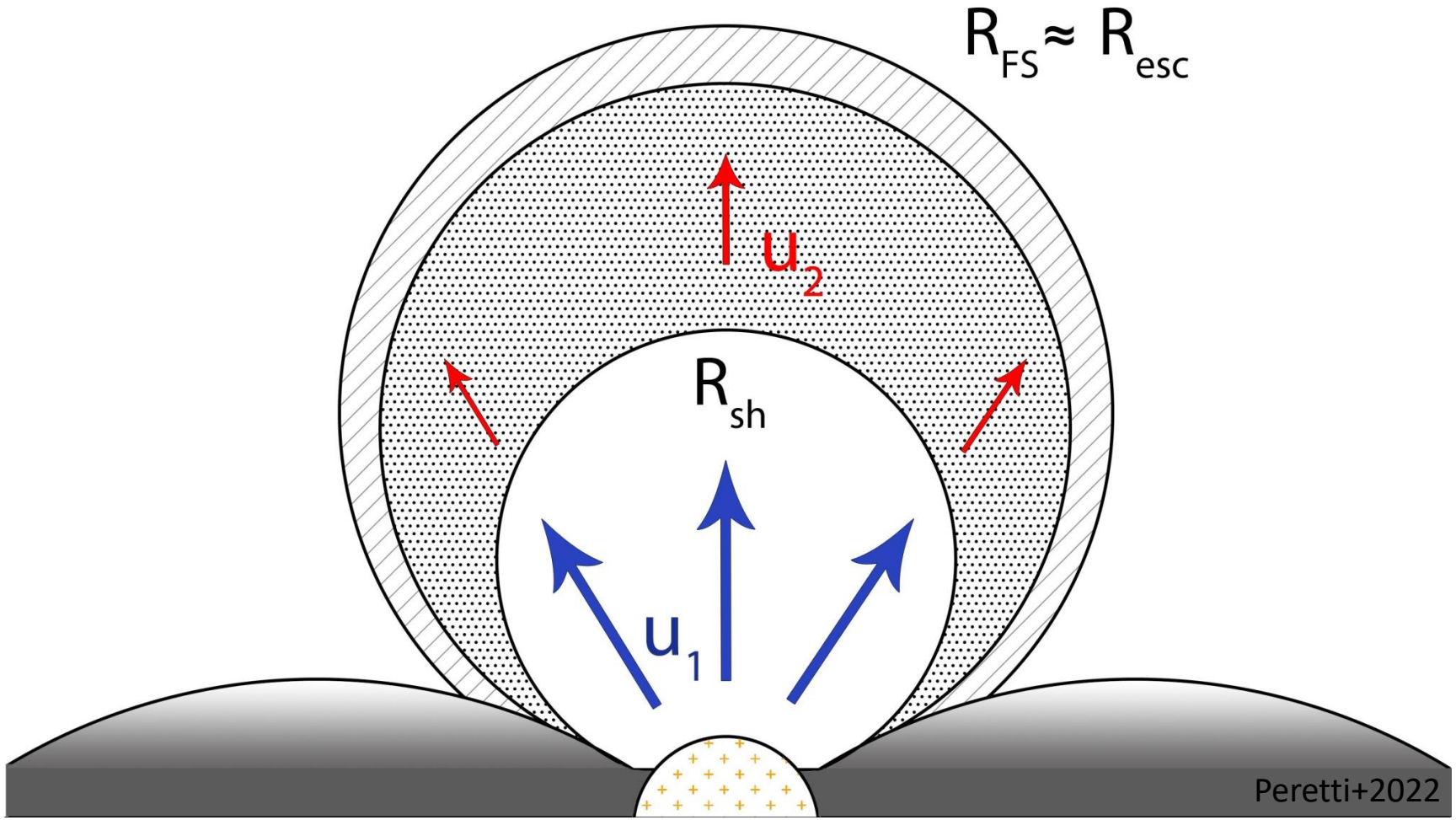


Transport model

$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \tfrac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2 \Lambda(r,p)$$



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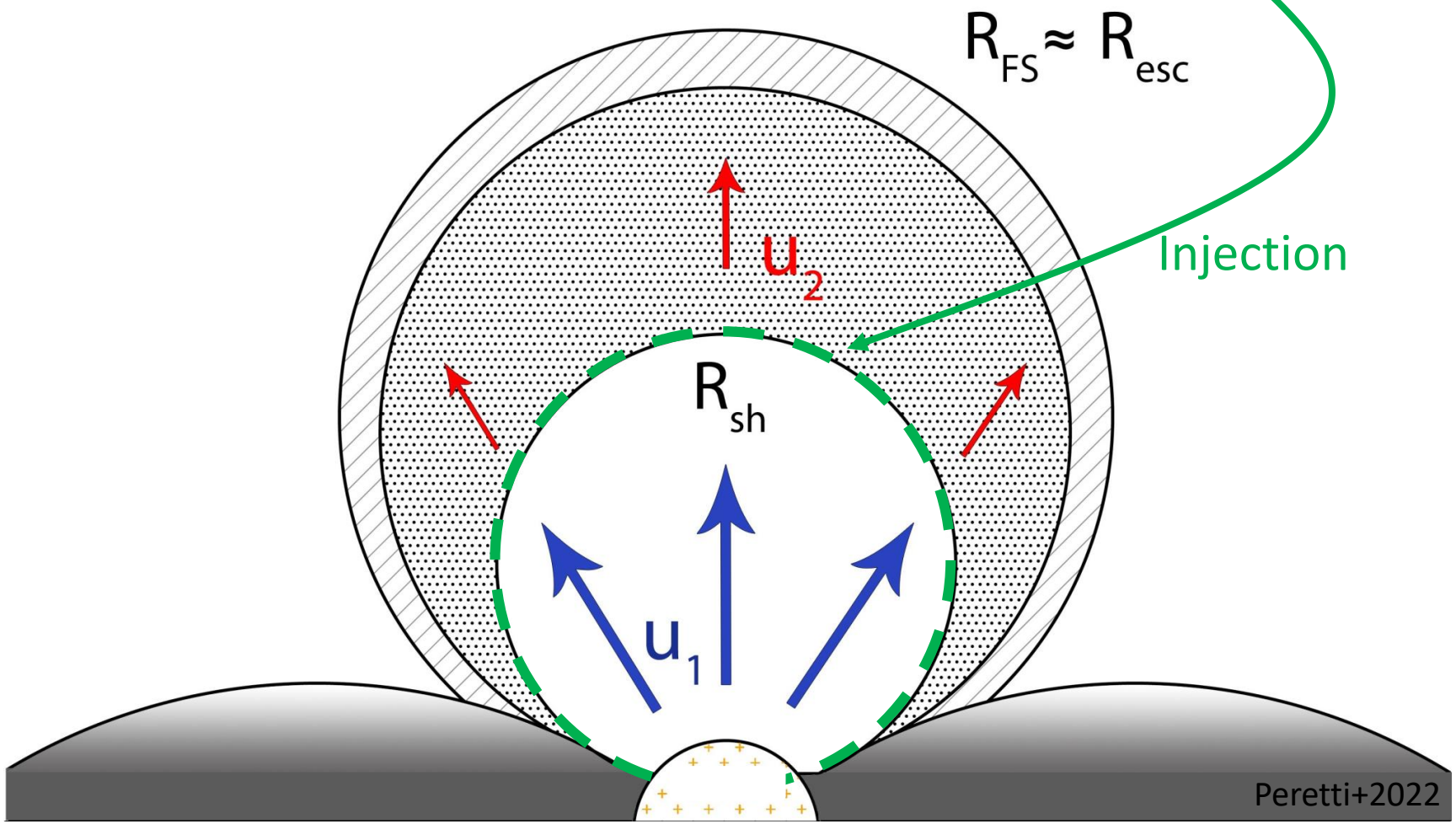

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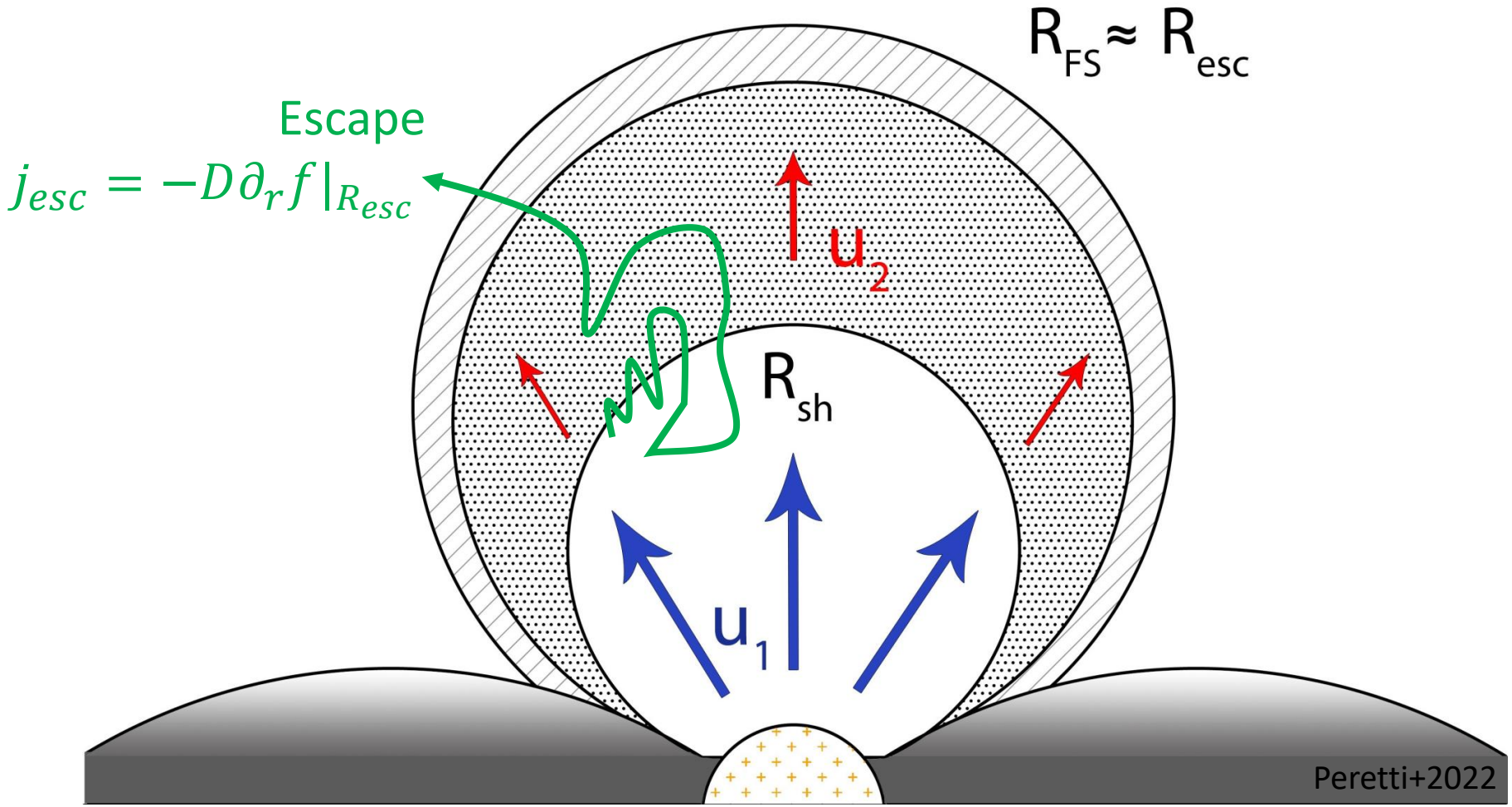

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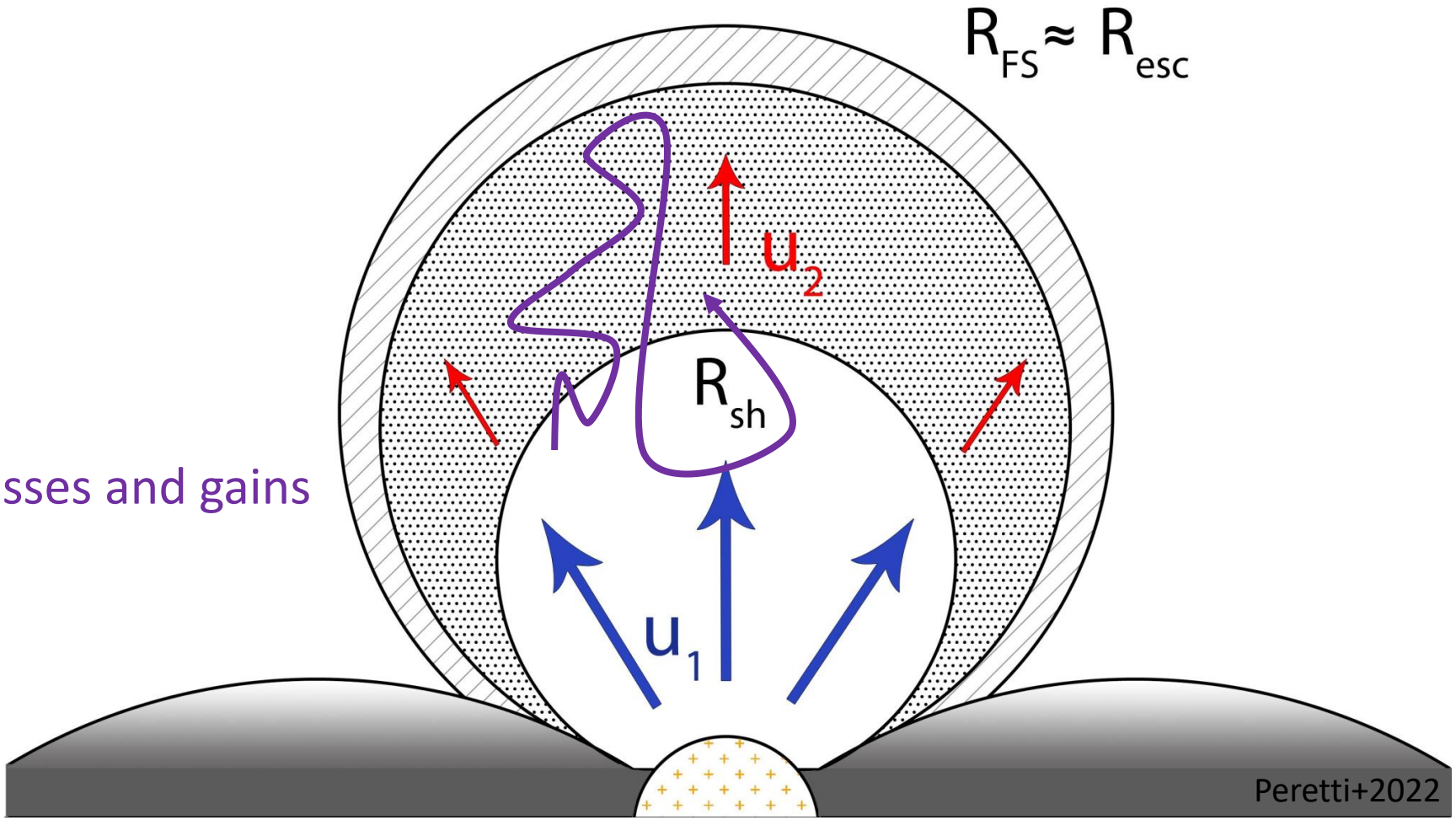
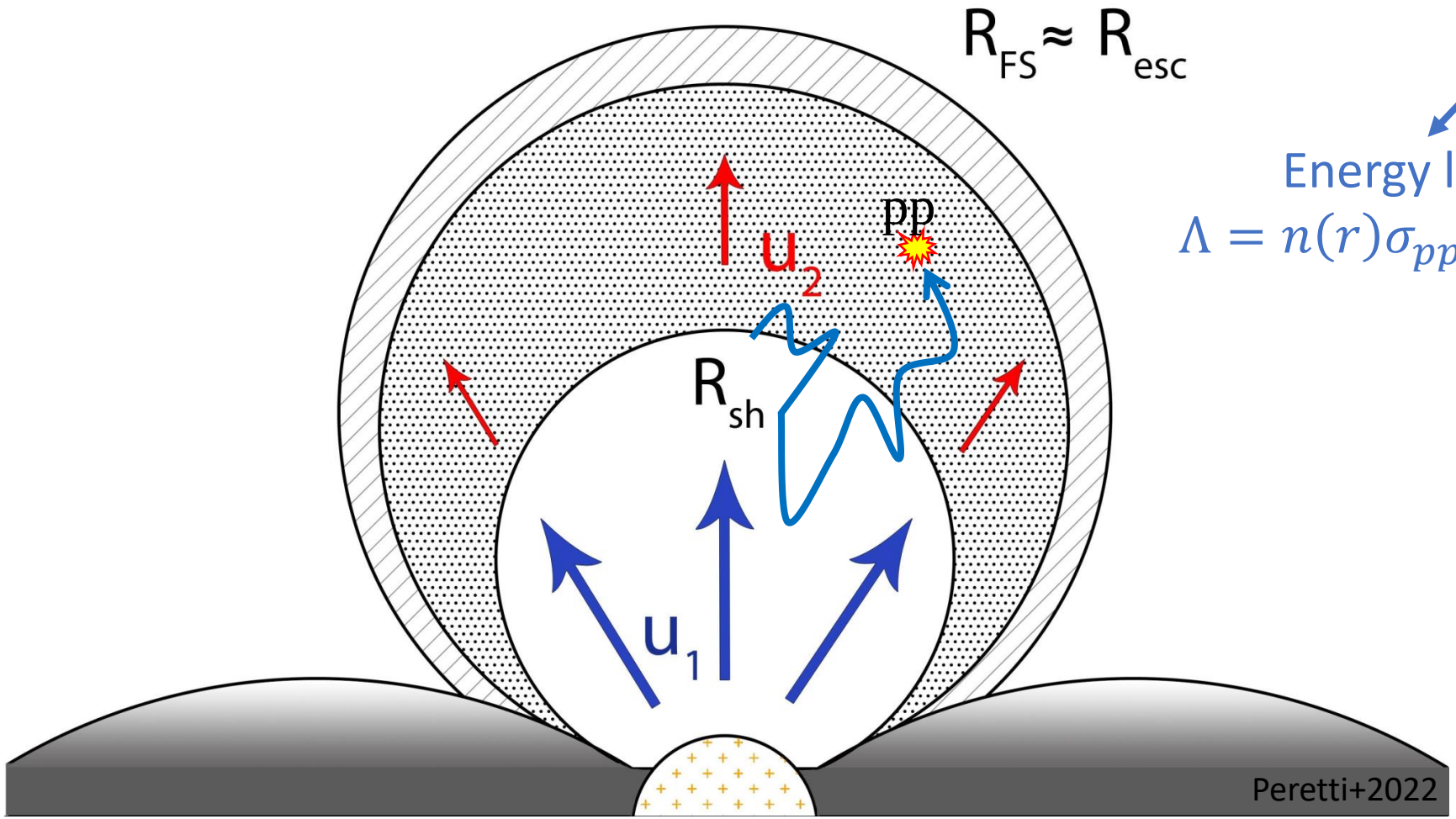
- Advection
- Diffusion
- Adiabatic losses and gains



Transport model

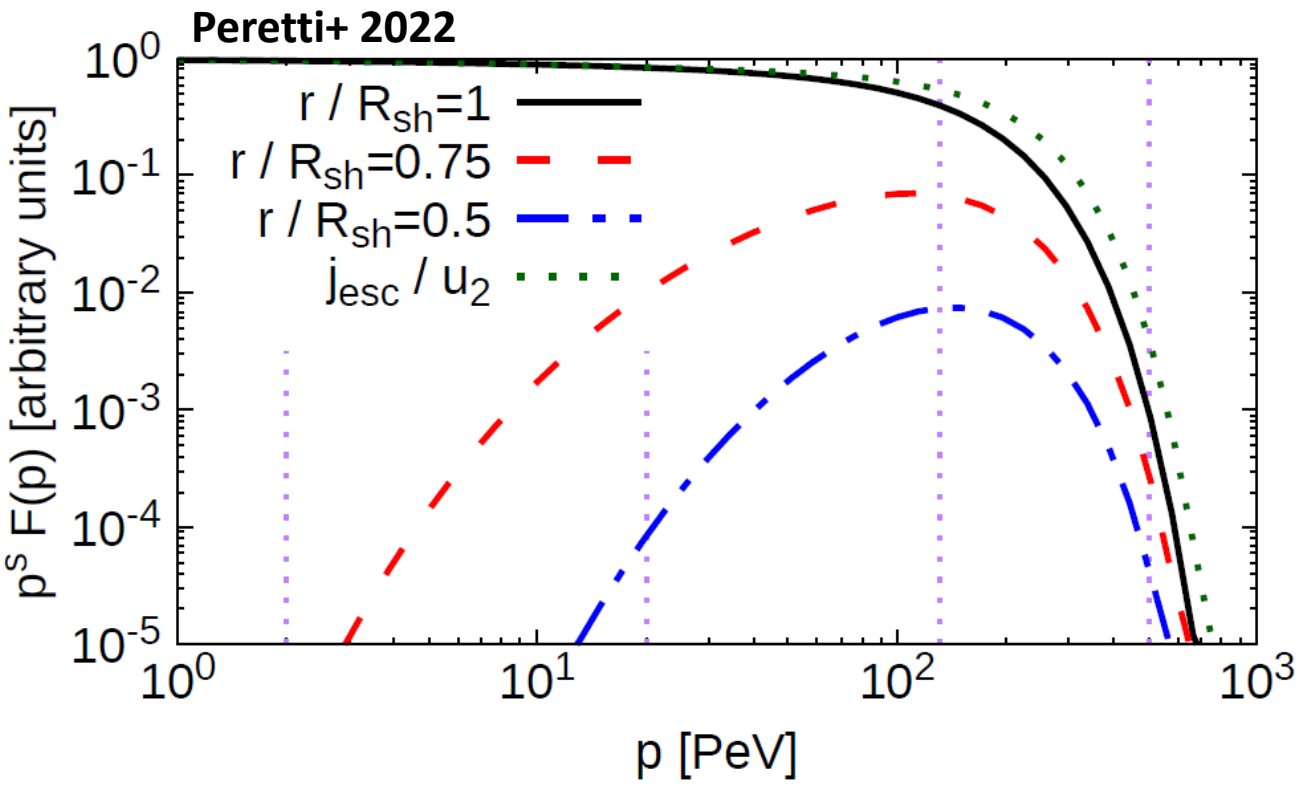
$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \tfrac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2\Lambda(r,p)$$



Energy losses

$$\Lambda = n(r)\sigma_{pp}(p)v(p)f$$

Particles in the system



Parameters

$\dot{M} = 10\ M_{\odot}\ yr^{-1}$

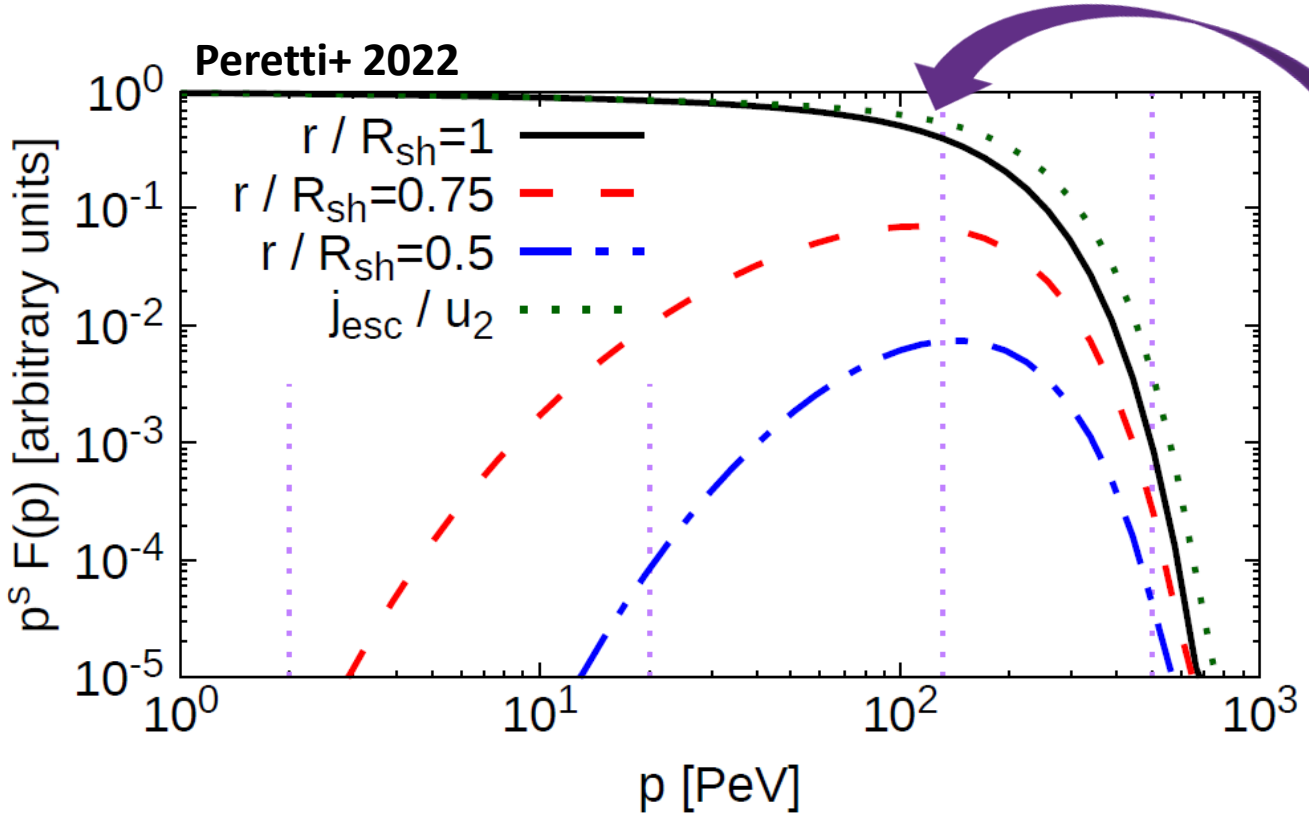
$V_{\infty} = 3000\ km\ \ s^{-1}$

$R_{sh} = 12\ kpc$

$R_{FS} = 55\ kpc$

$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

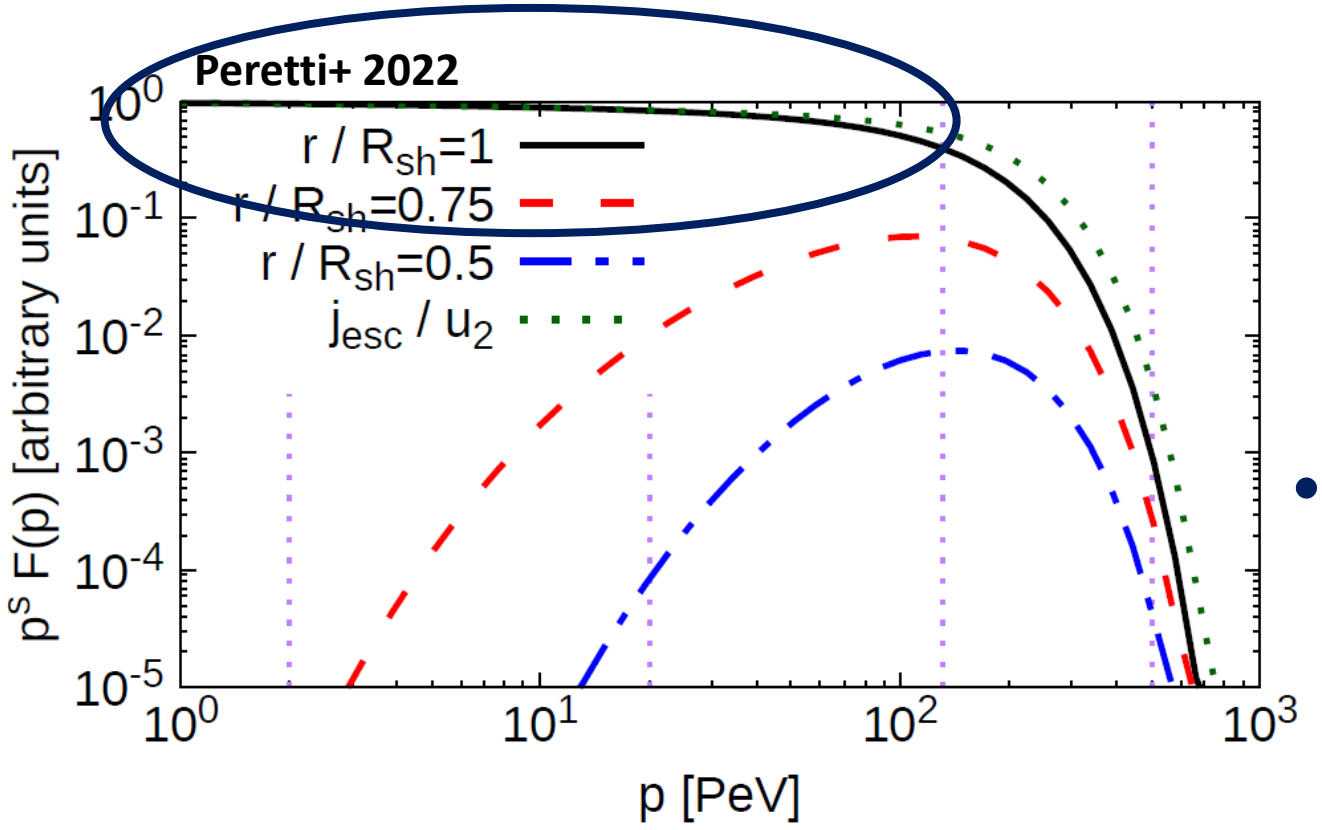
Particles in the system



- Maximum Energy → 10^2 PeV

$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

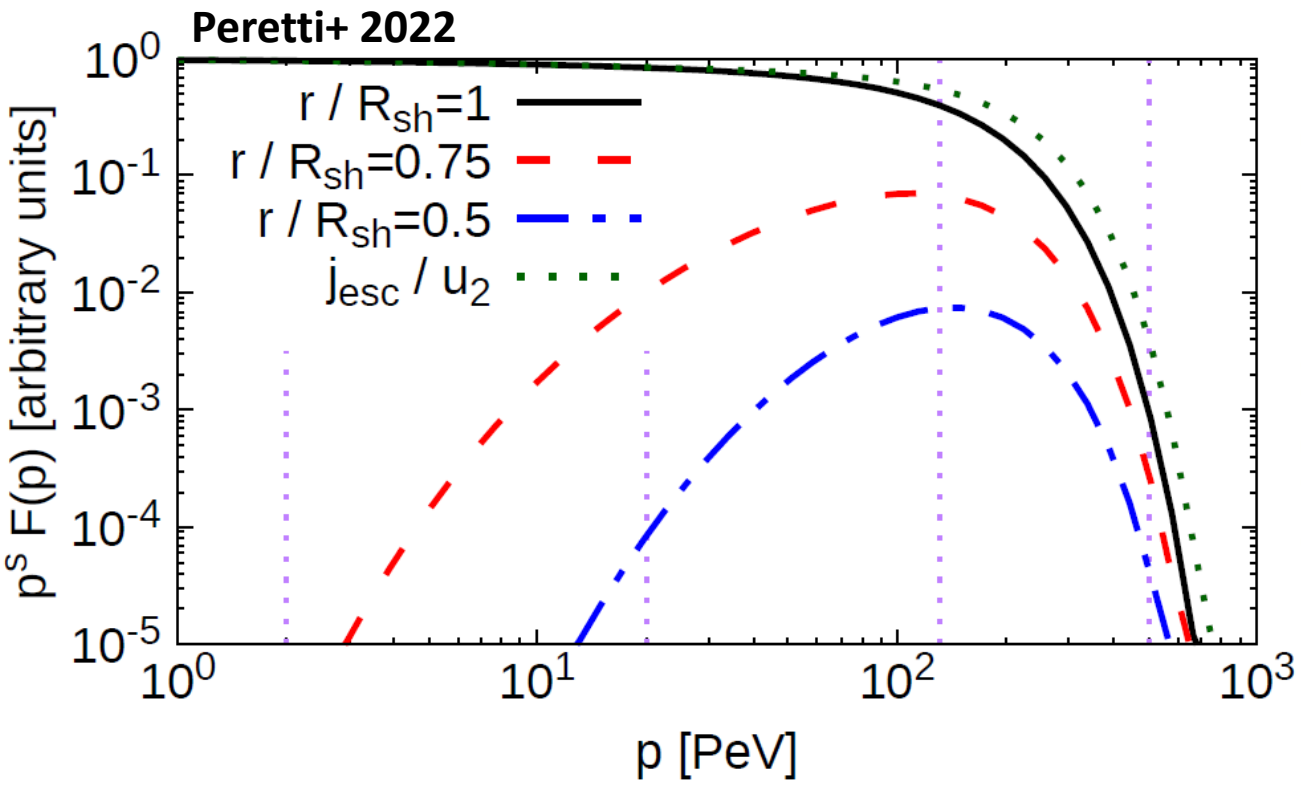
Particles in the system

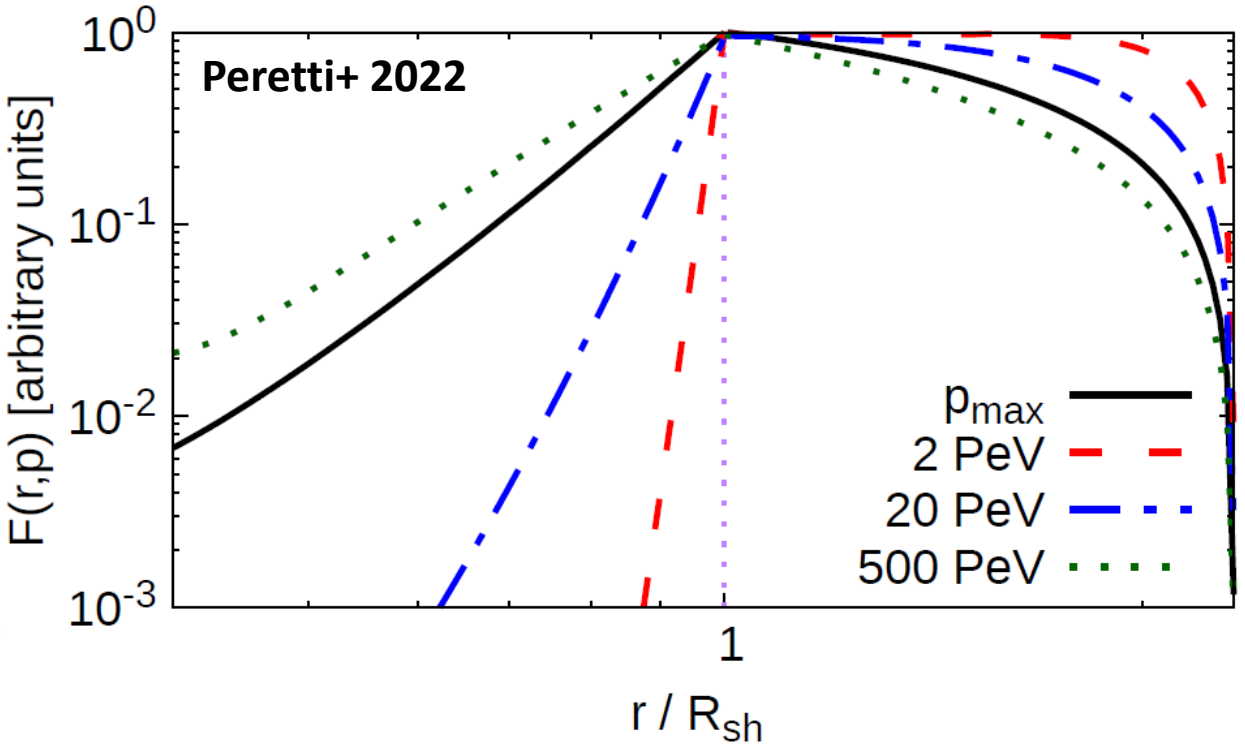


- Maximum Energy → 10^2 PeV
- Standard DSA valid at low Energy

$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

Particles in the system

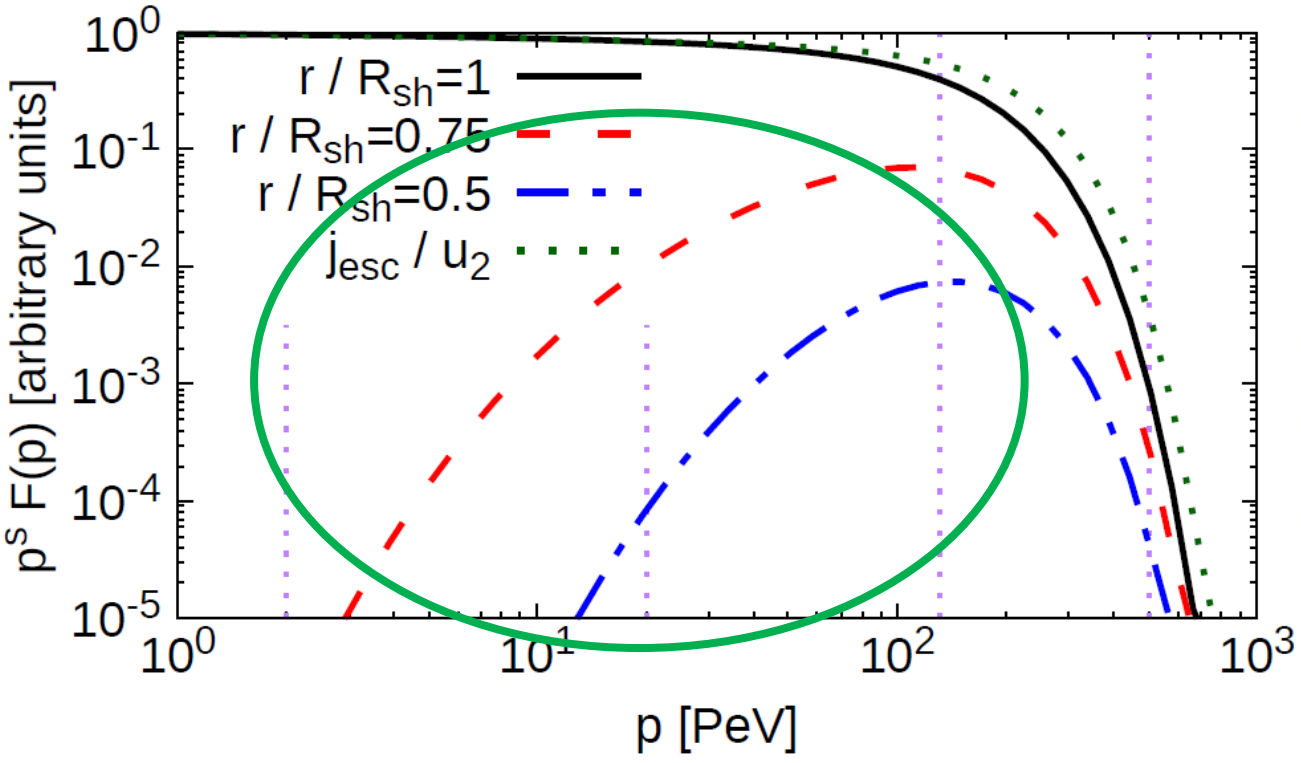


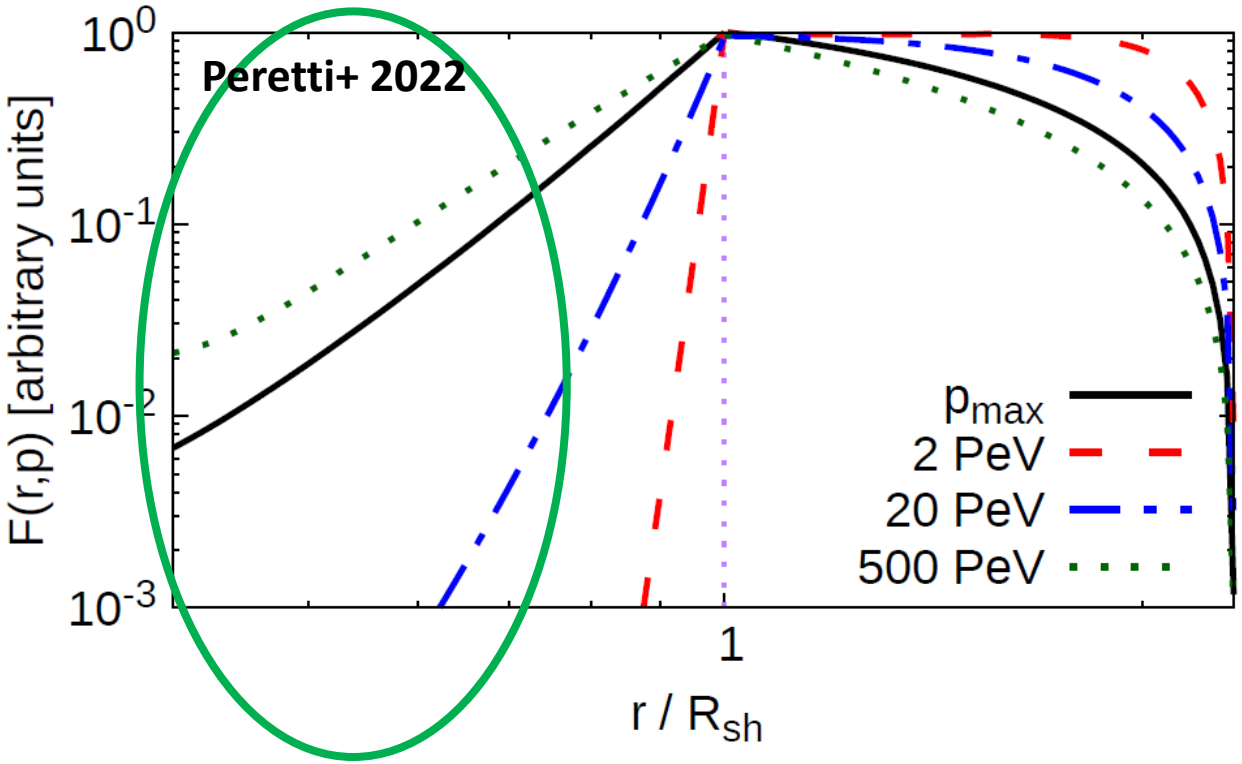


$$f_{sh}(p) \propto p^{-s} e^{-\Gamma_1(p)} e^{-\Gamma_2(p)}$$

$$f_u(r,p) = f_{sh}(p)\, e^{-\int_r^{R_{sh}} \left(\frac{u_{eff}}{D}\right) dr'}$$

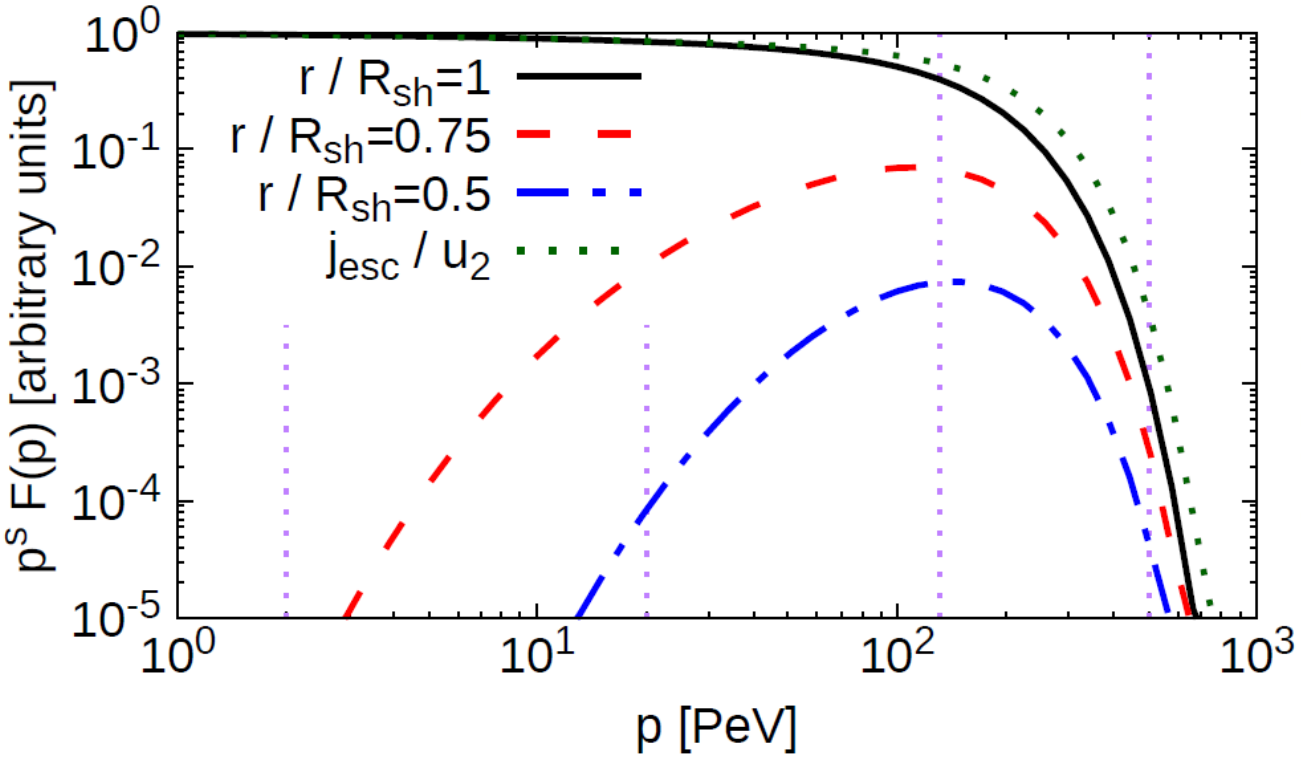
Particles in the system

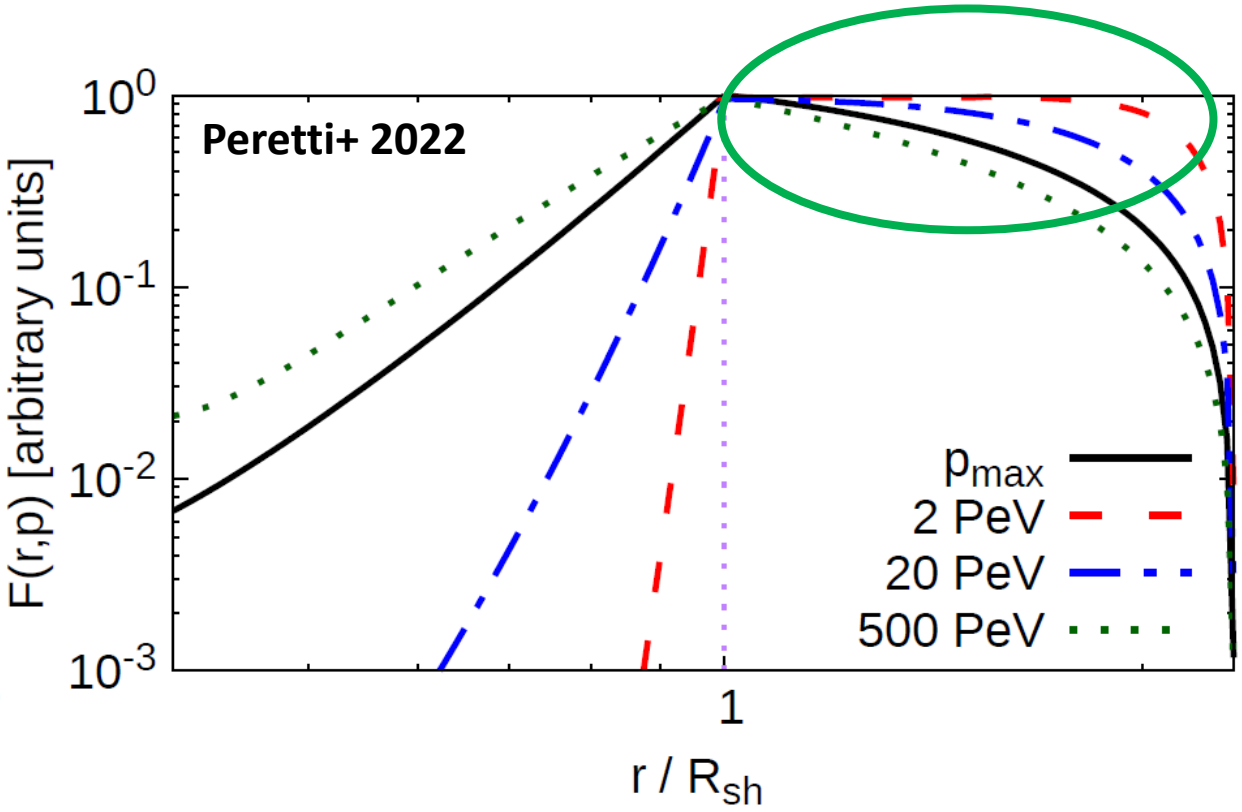




The wind suppresses the diffusion of particles back to the galaxy

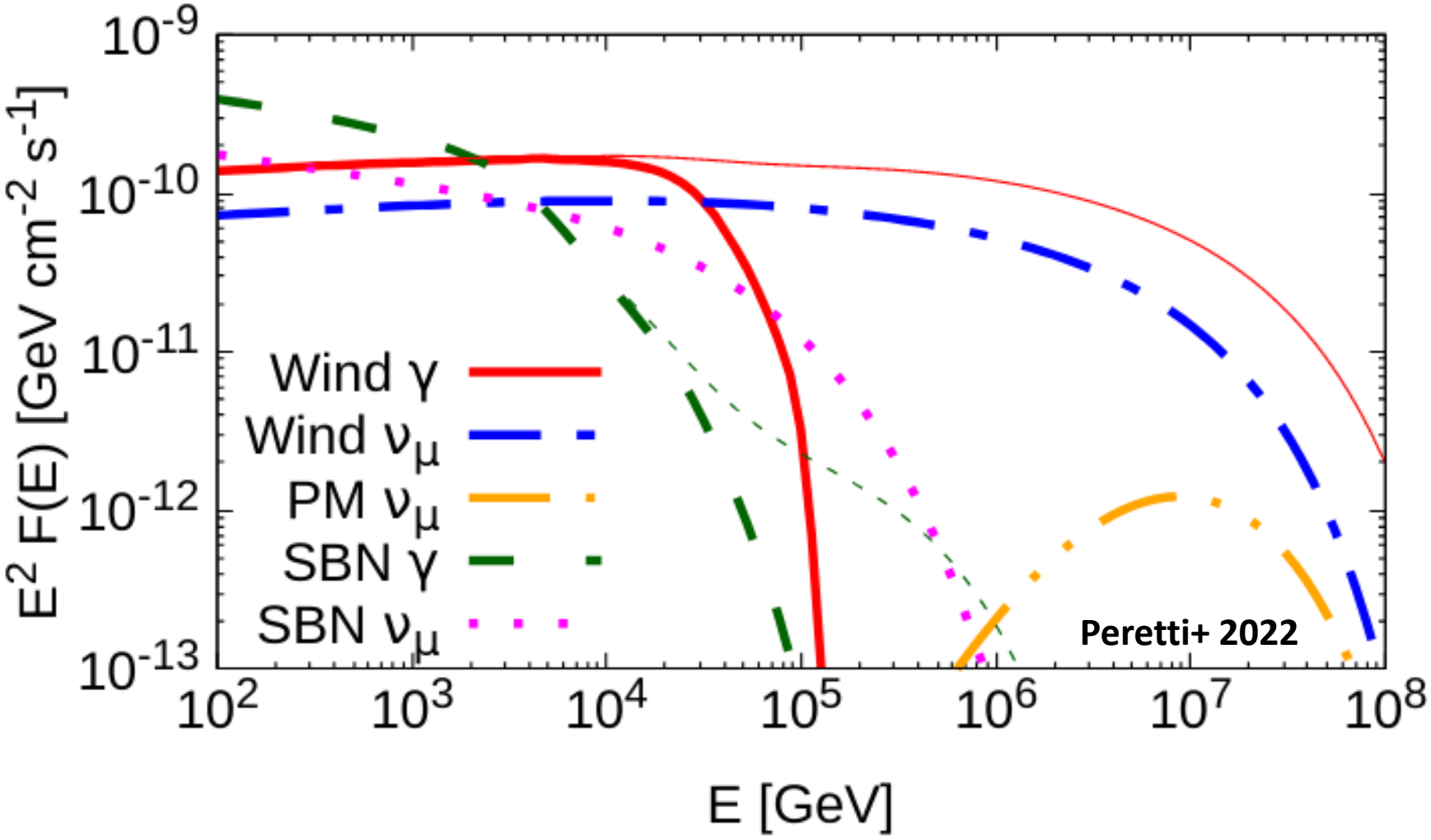
Particles in the system



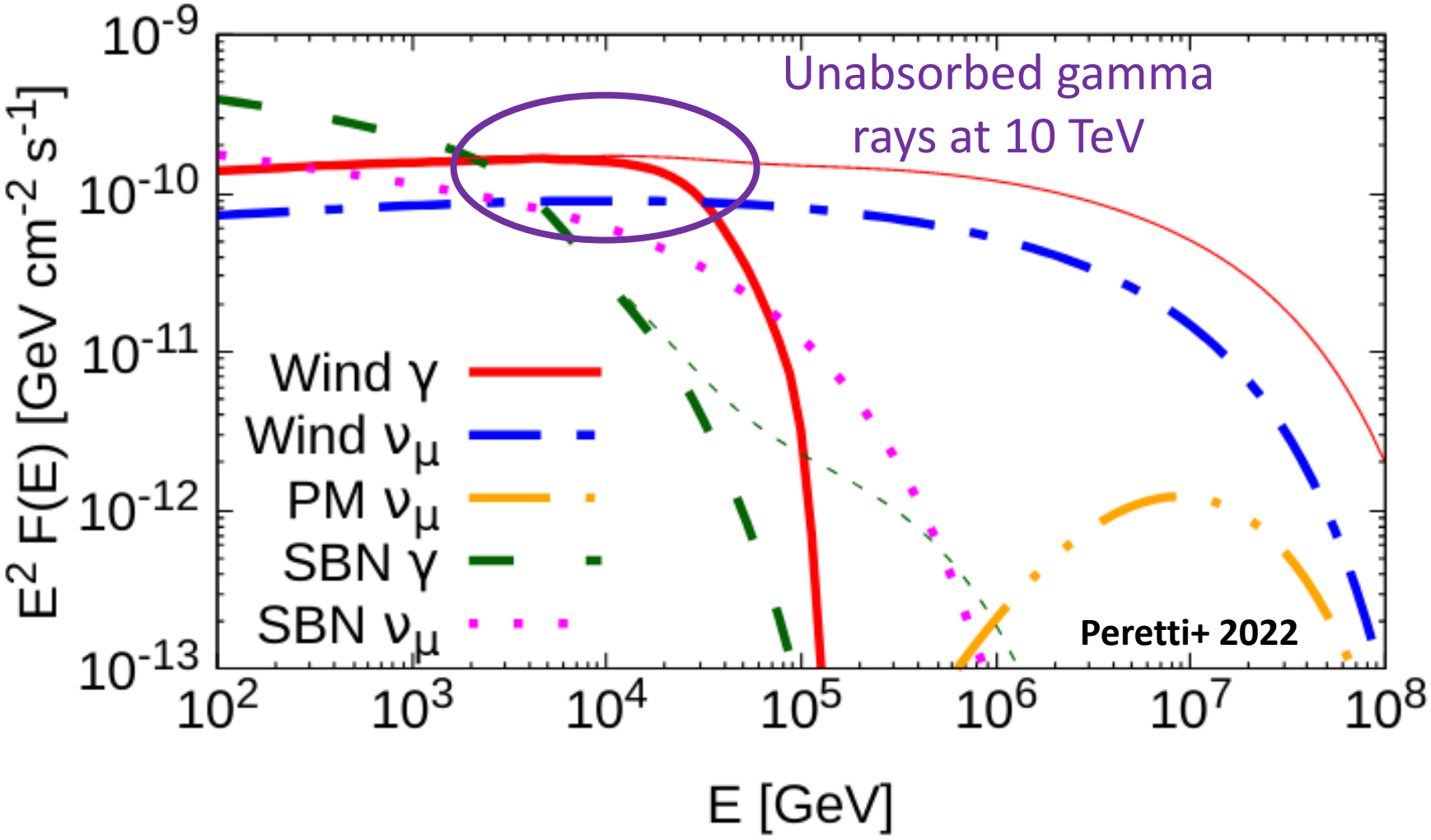


Particle distribution homogenized in the downstream region

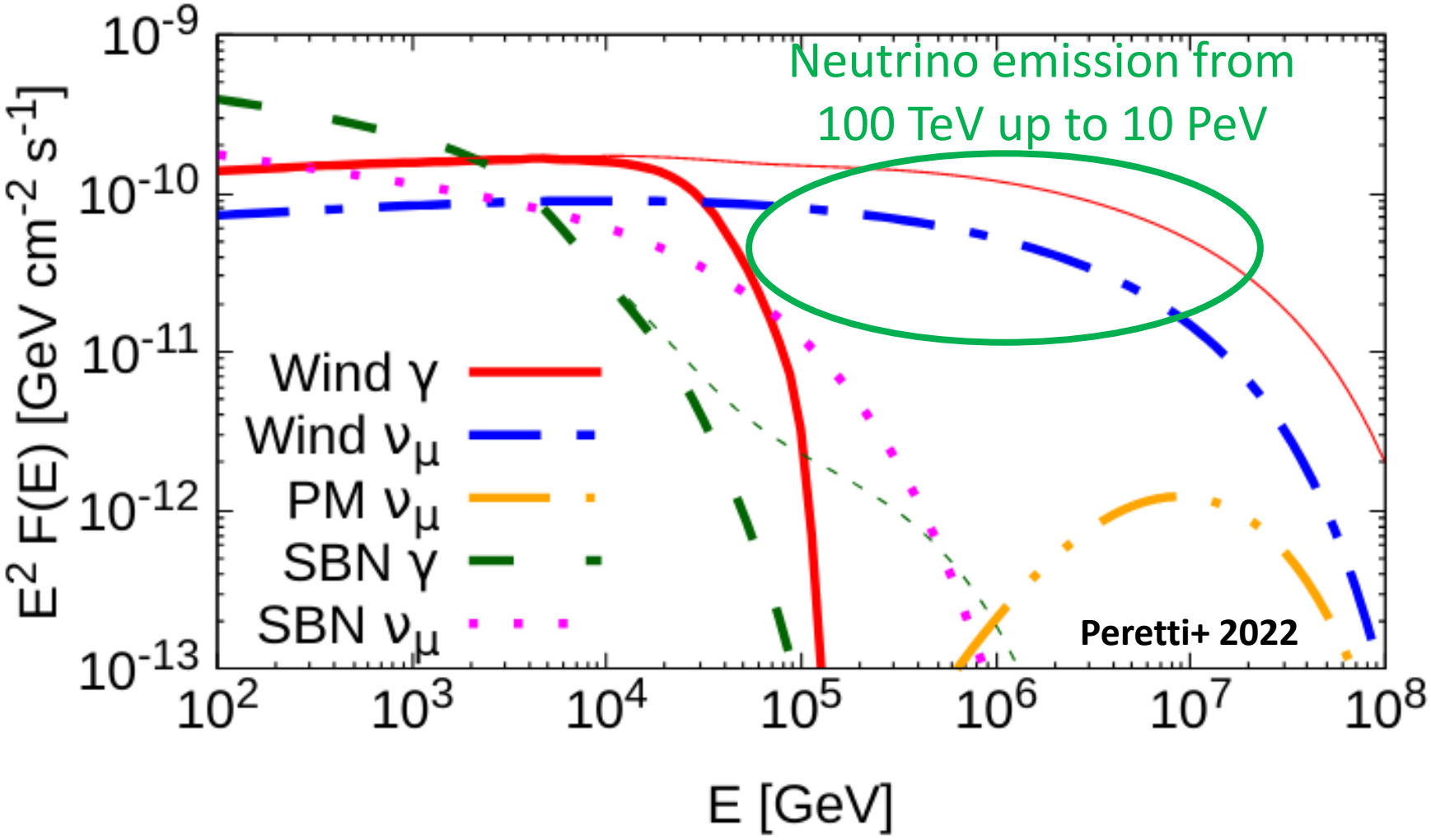
High-Energy SED and Neutrinos



High-Energy SED and Neutrinos



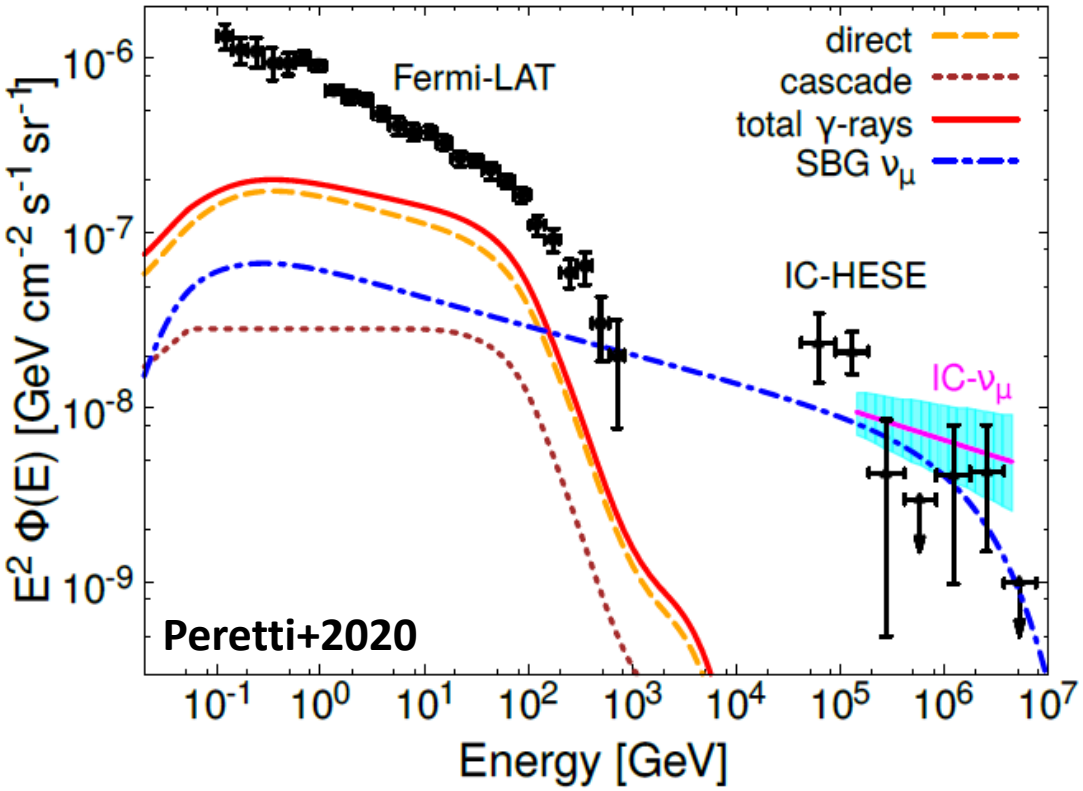
High-Energy SED and Neutrinos



Outline

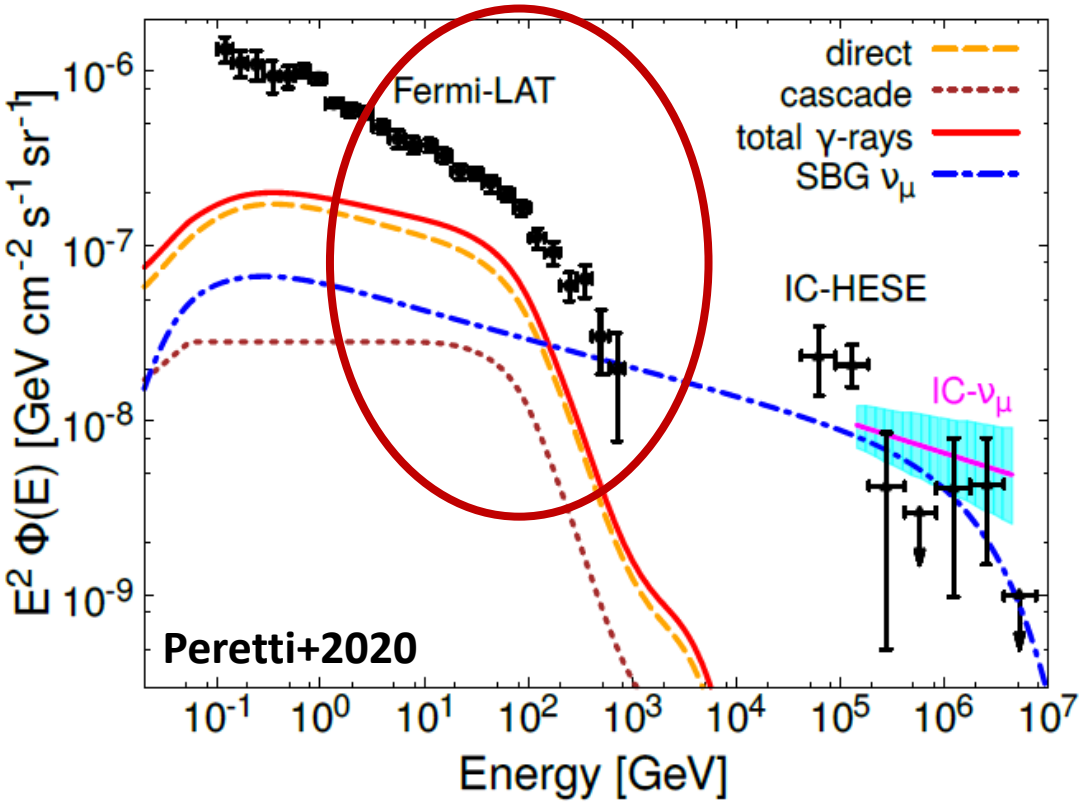
- Observations of Starburst Galaxies
- Particle Transport in Starburst Nuclei
- Acceleration and transport in starburst-driven winds
- Diffuse emission from Starburst Galaxies

Diffuse emission from Starburst Galaxies



- SBNi only

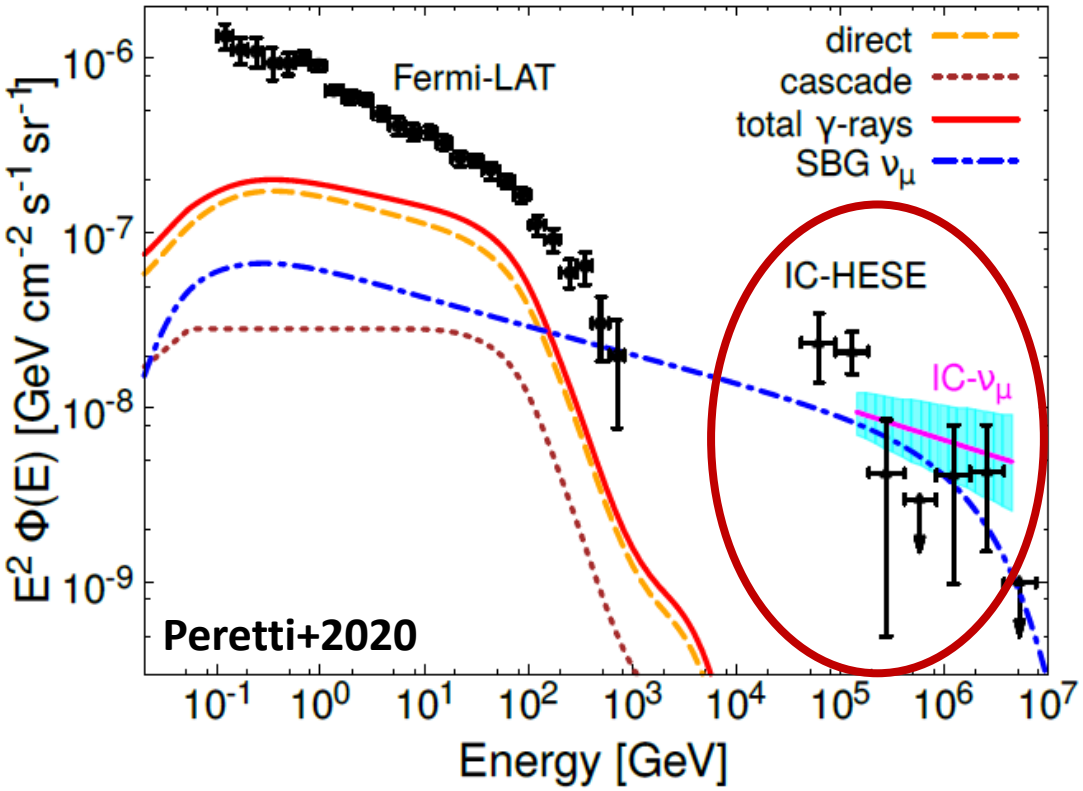
Diffuse emission from Starburst Galaxies



- SBNi only

- Sizeable contribution to the diffuse flux observed by Fermi-LAT

Diffuse emission from Starburst Galaxies



- SBNi only
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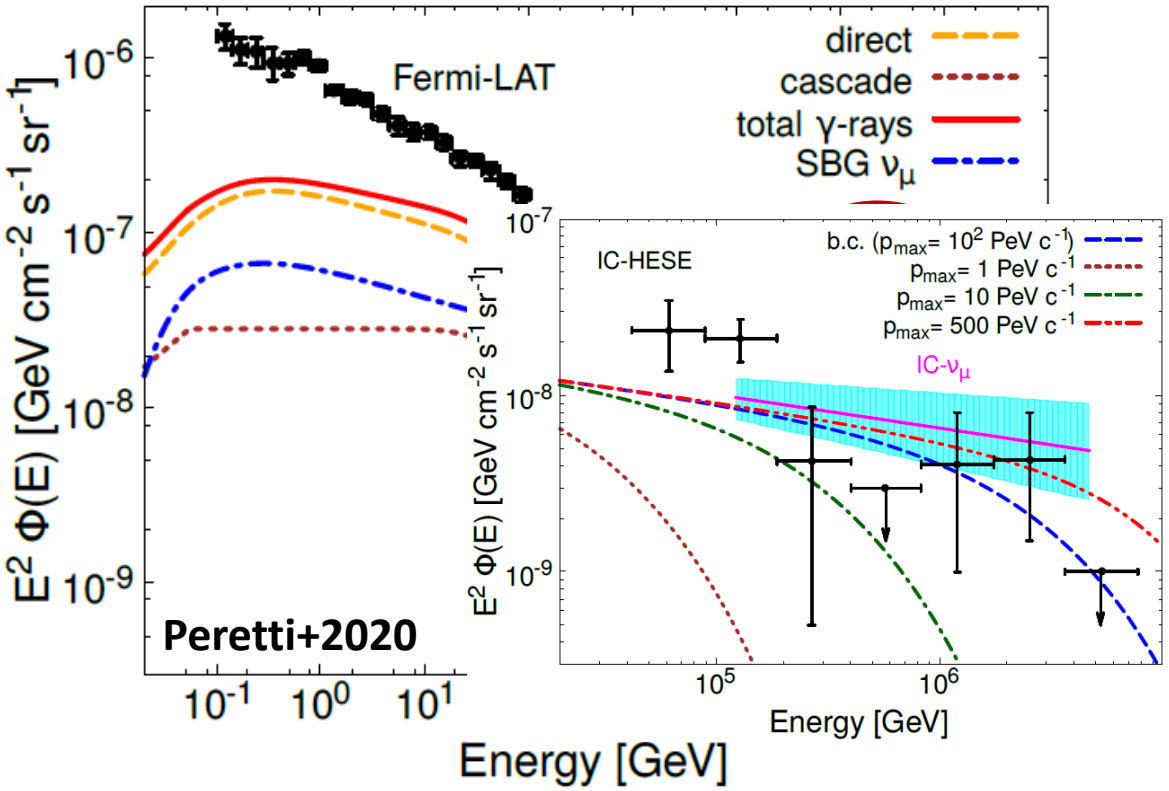
- Neutrino flux at the level of IceCube measurment

Diffuse emission from Starburst Galaxies



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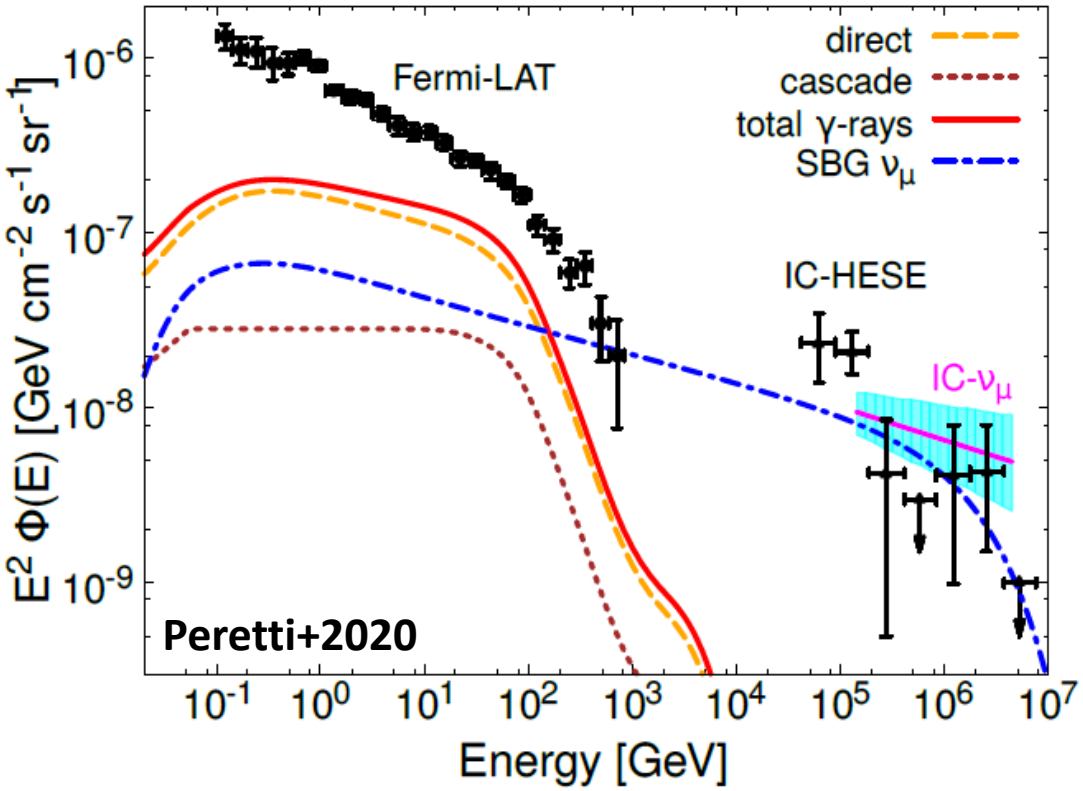
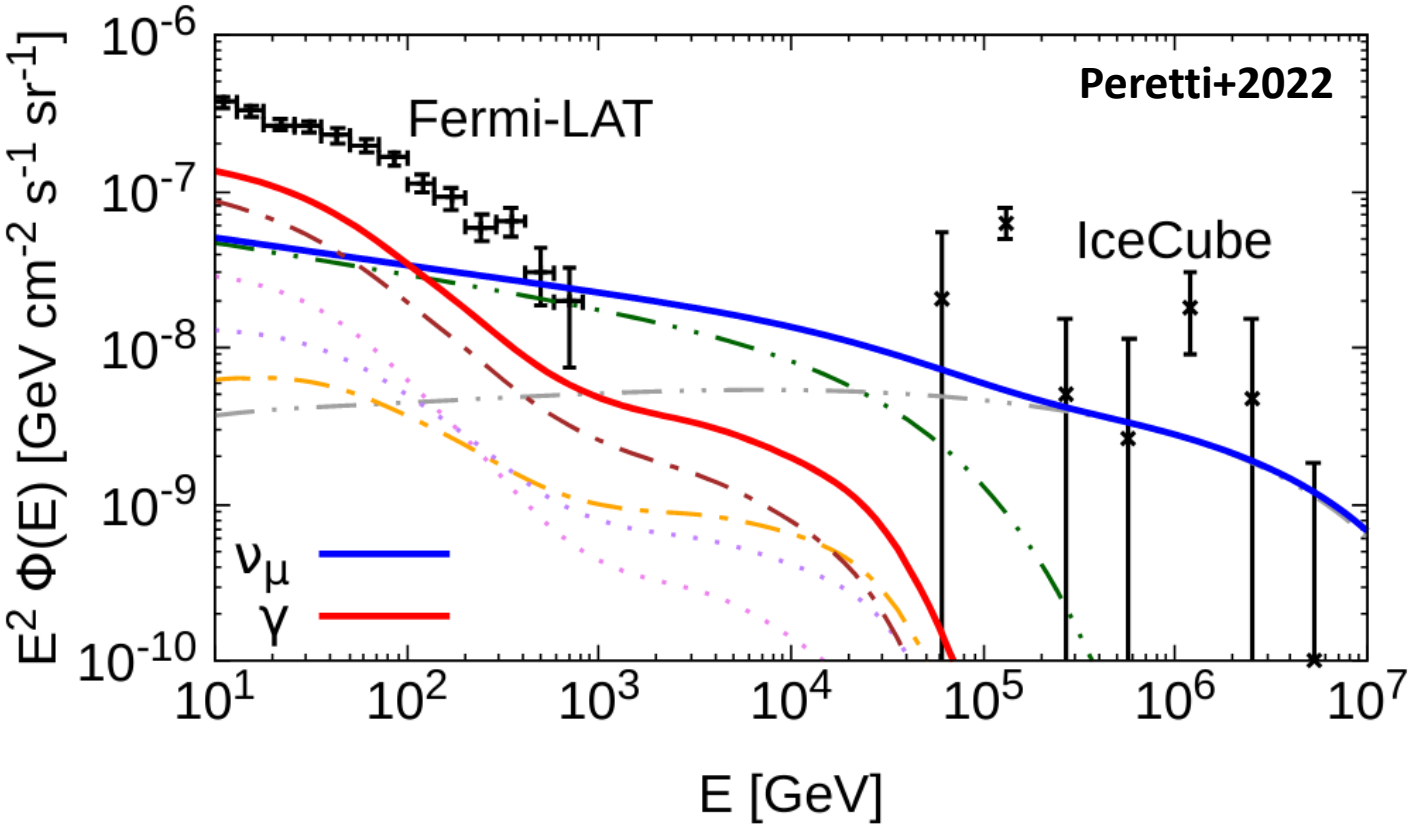
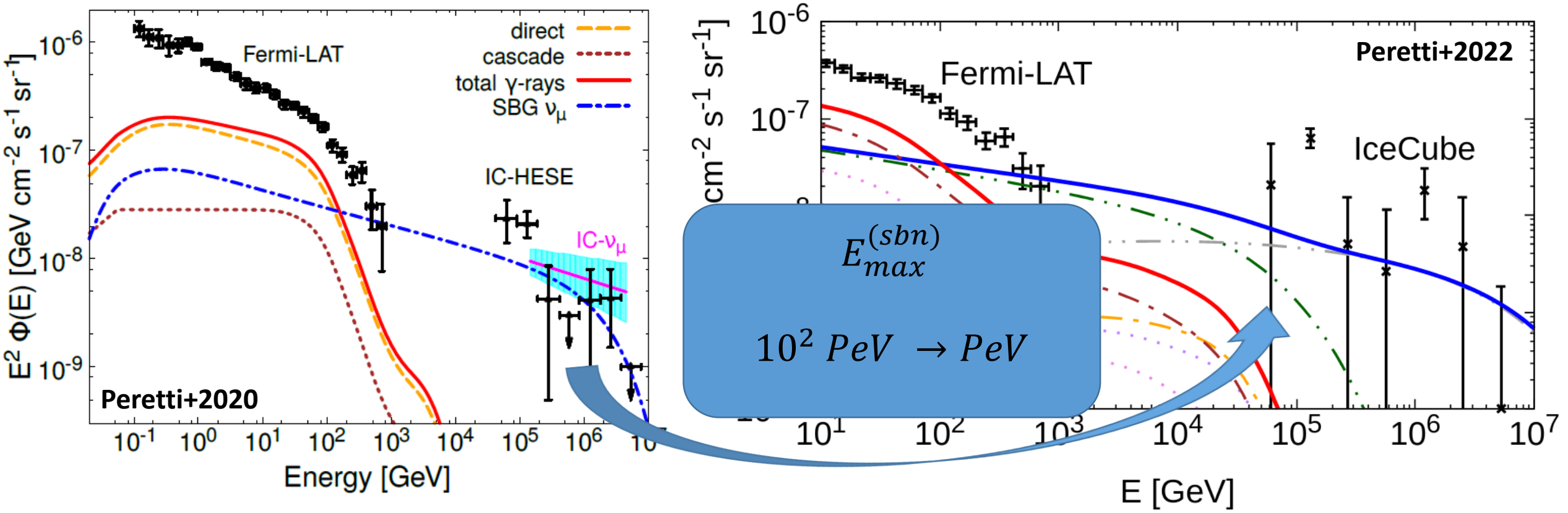
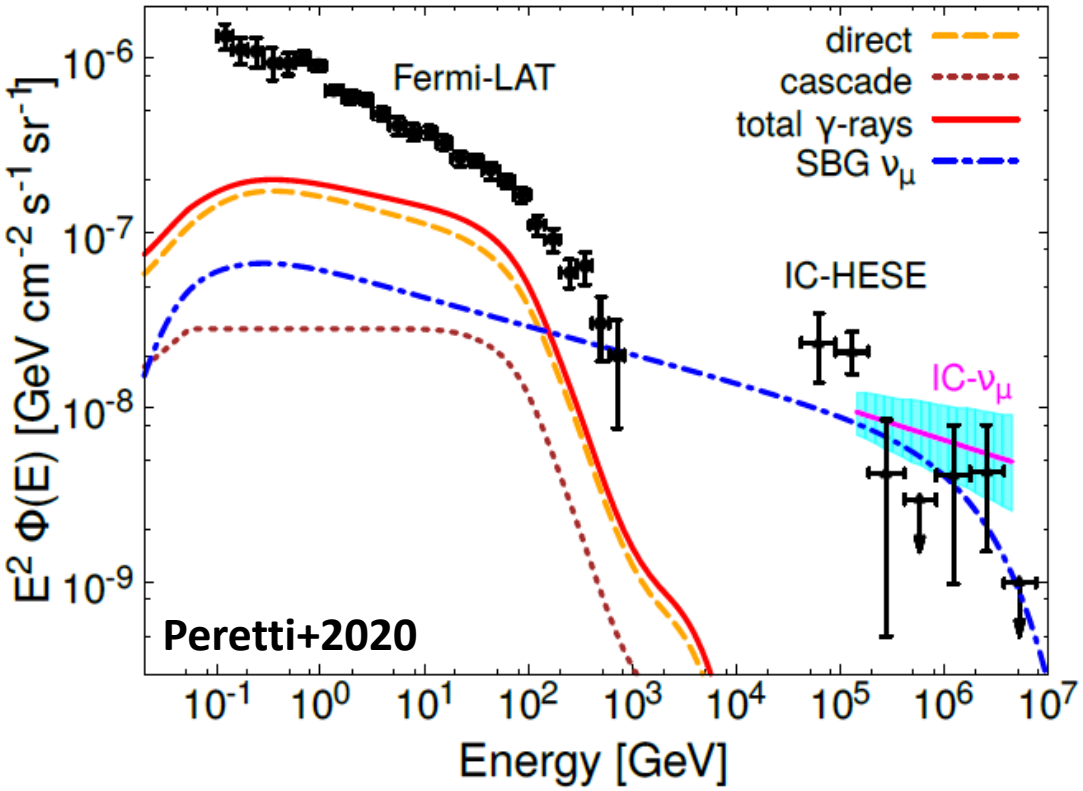


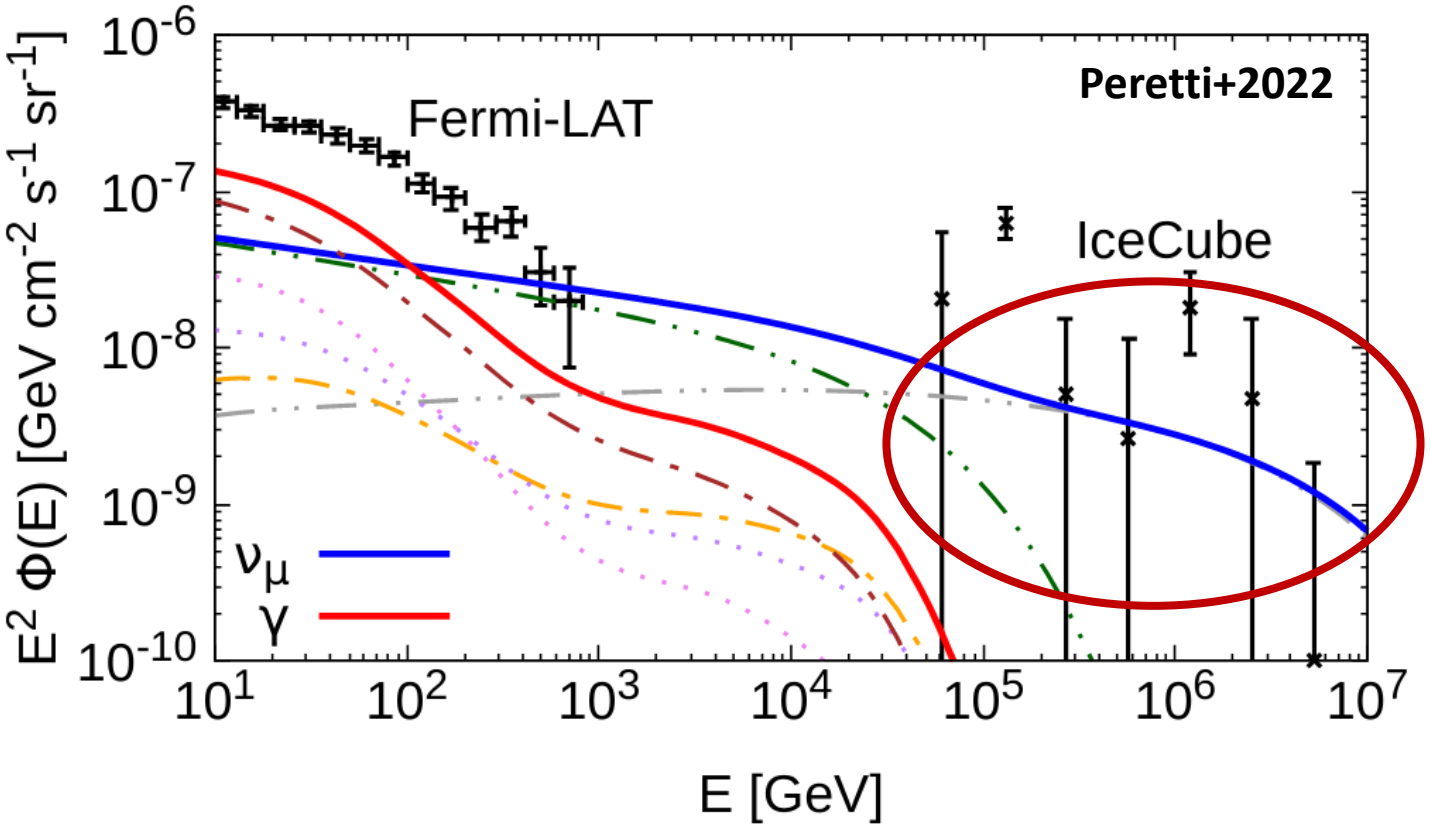


Diffuse emission from Starburst Galaxies

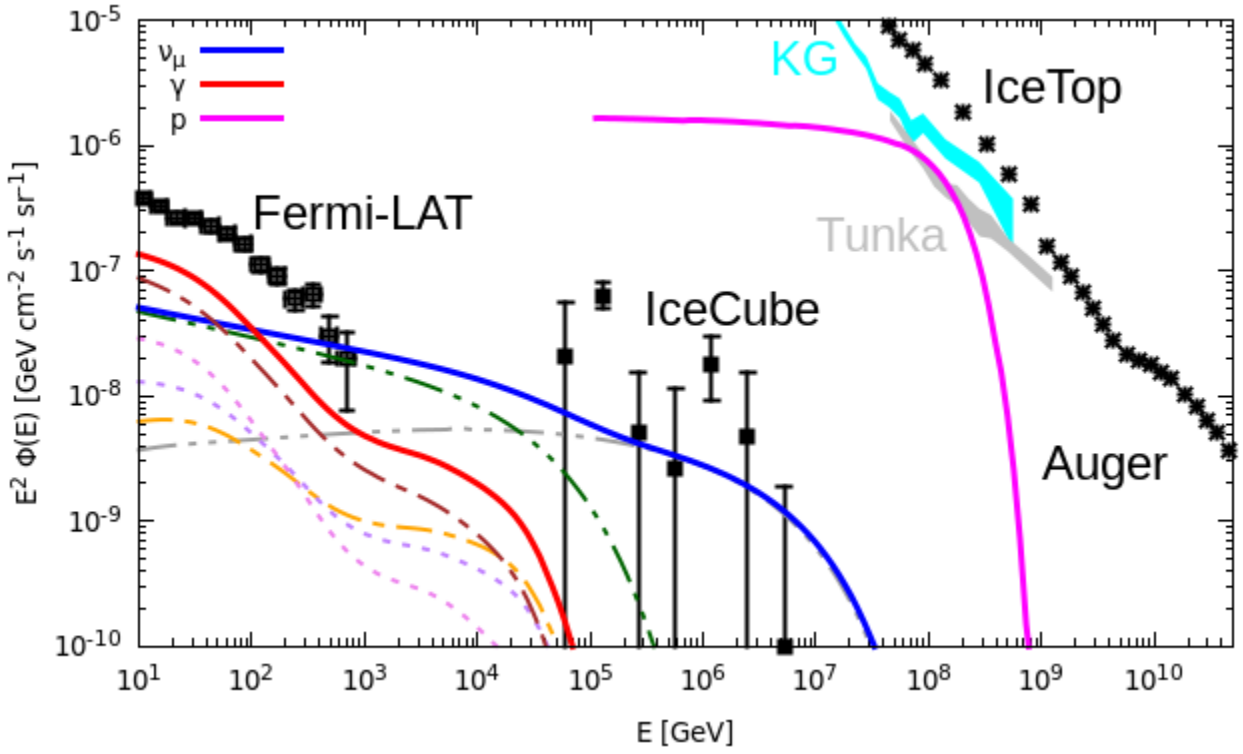


Diffuse emission from Starburst Galaxies

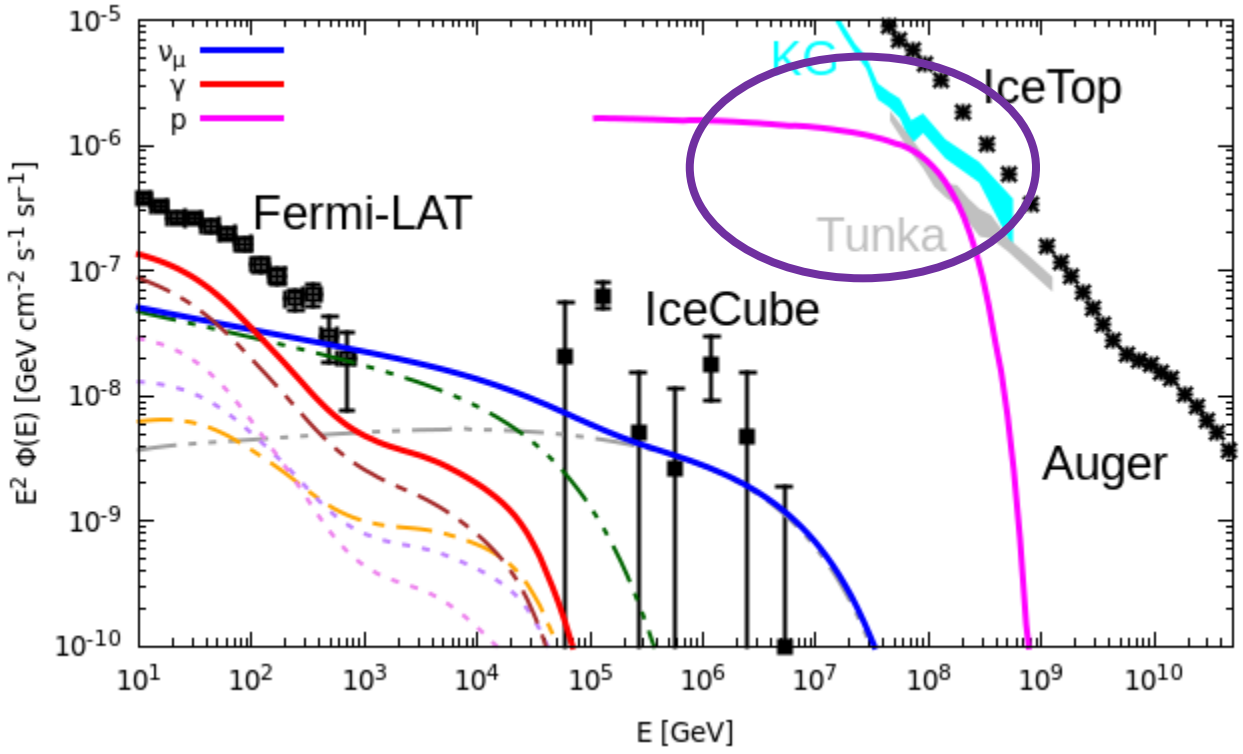


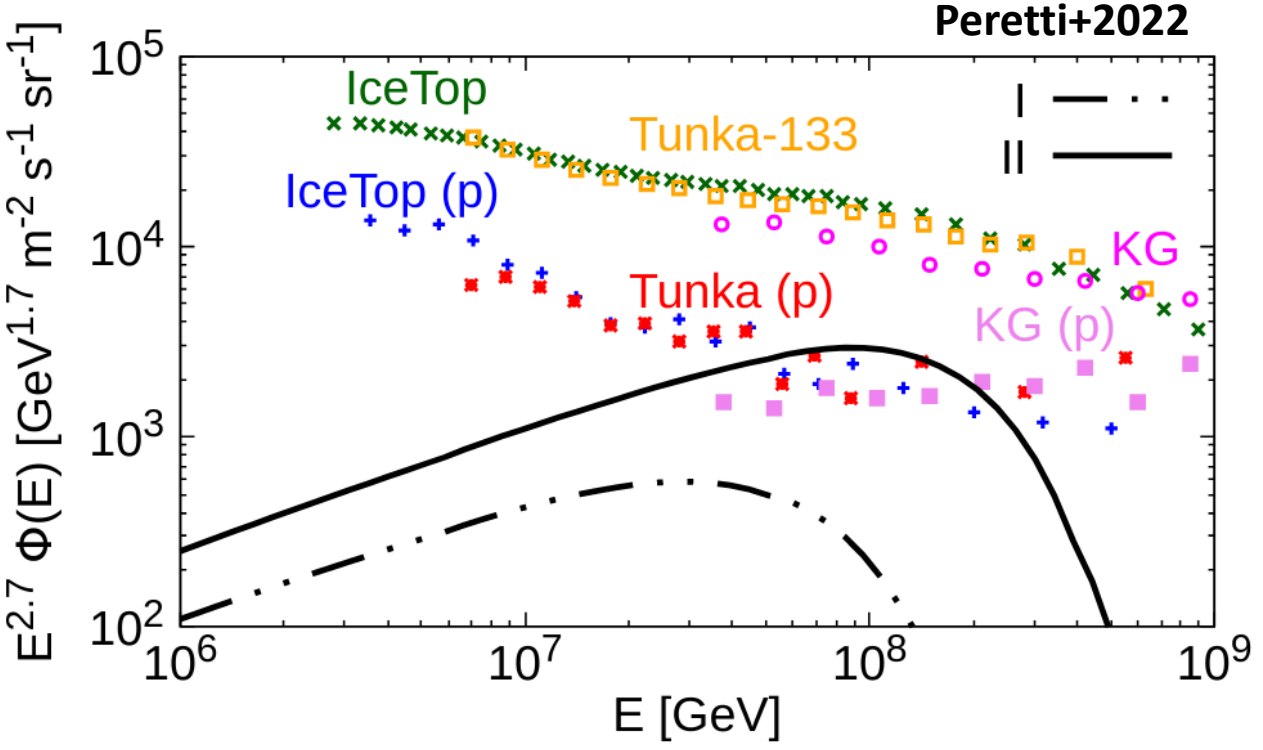


Multimessenger emission from Starburst Galaxies



Multimessenger emission from Starburst Galaxies

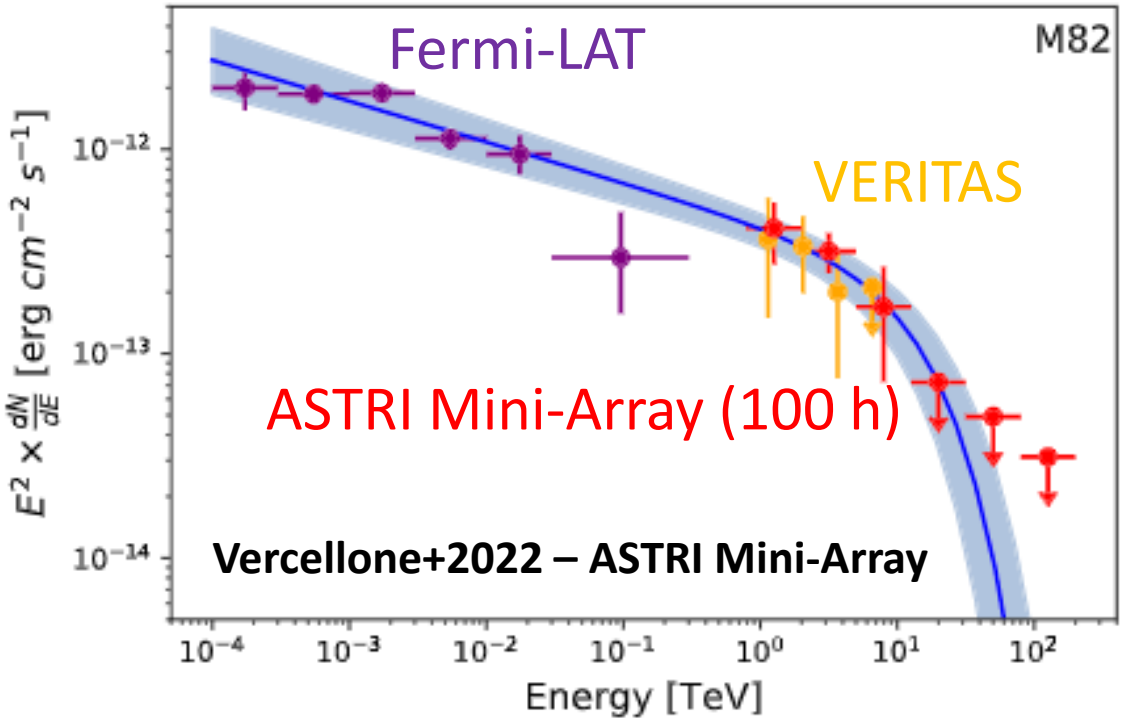


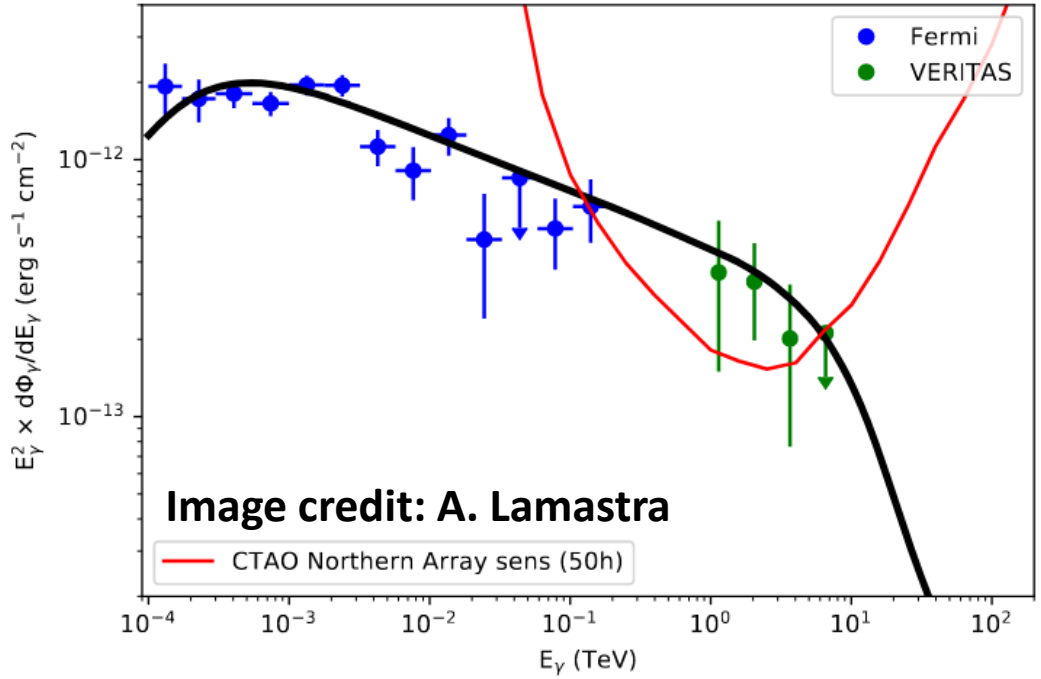


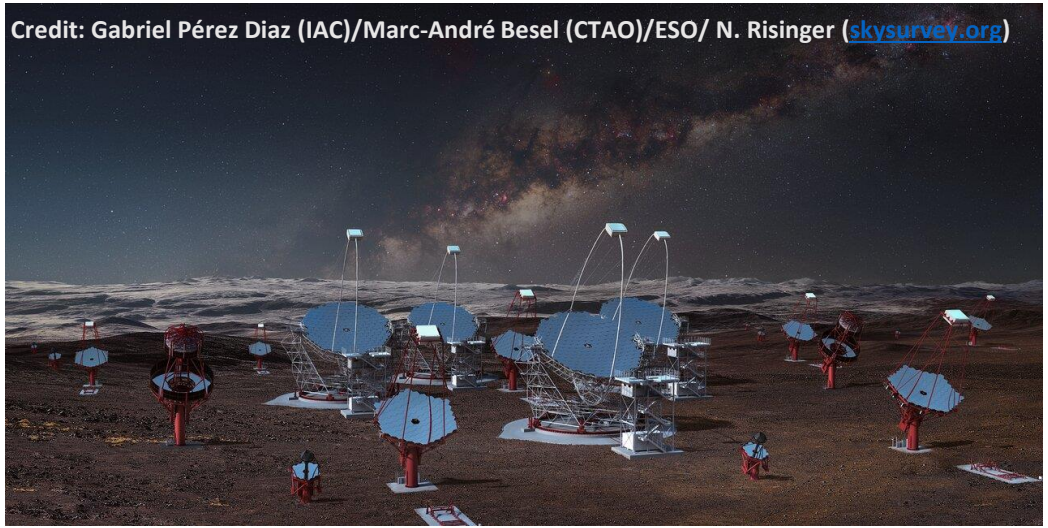
Take home messages

- Starburst galaxies can approach calorimeteric conditions
- We expect gamma rays and neutrino both from SBNi and wind
- Starburst can provide a sizeable contribution to the multimessenger diffuse flux (CRs, gamma rays, neutrinos)
- New observatories are coming → promising observation perspectives!

Upcoming gamma-ray observations





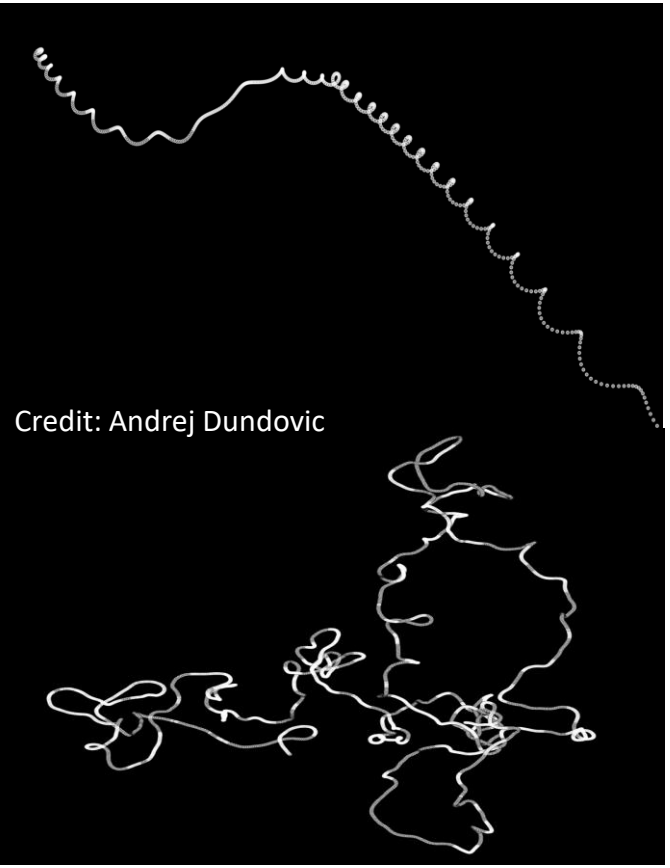


Outlook and open questions

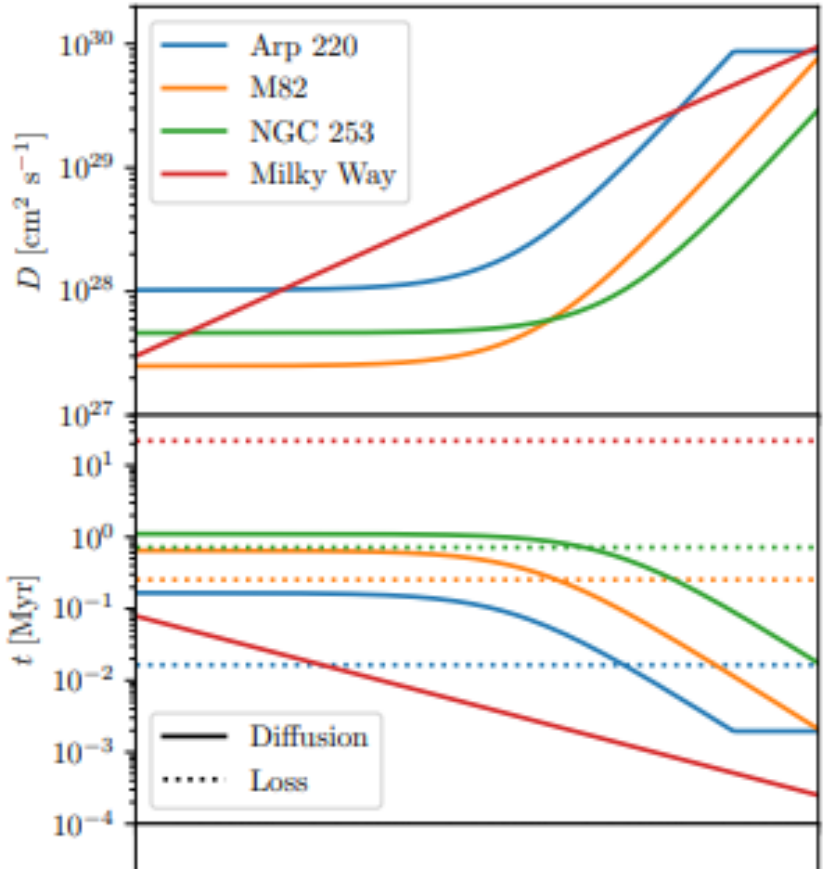
- Transport and diffusion: neutral medium?

Outlook and open questions

- Transport and diffusion: neutral medium?



Krumholtz+2020



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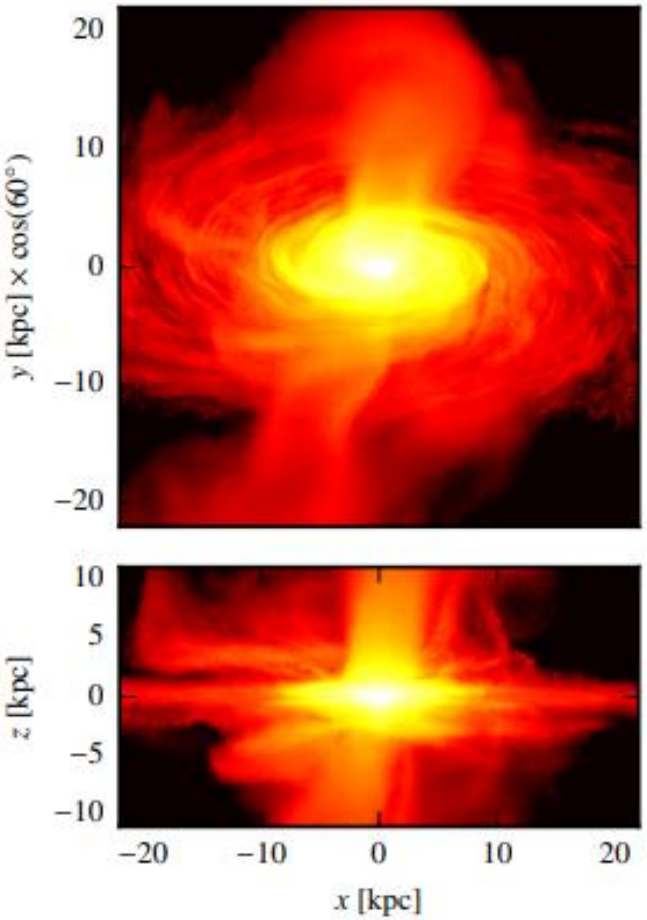
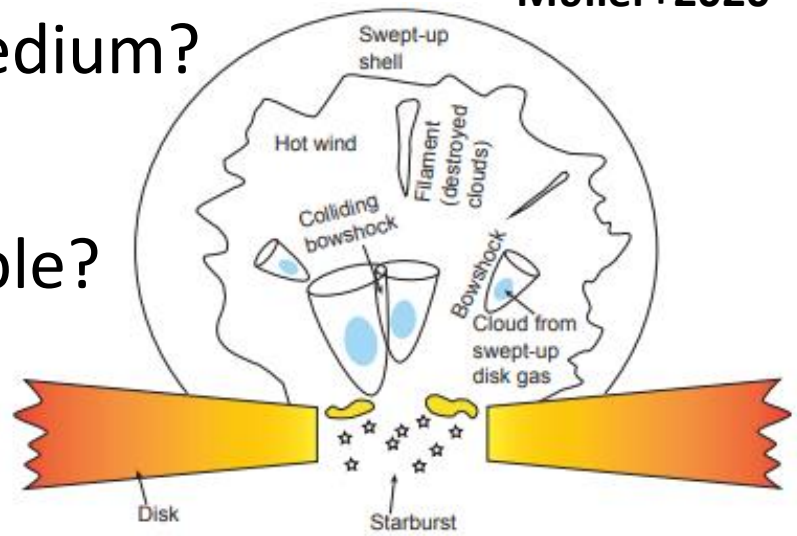
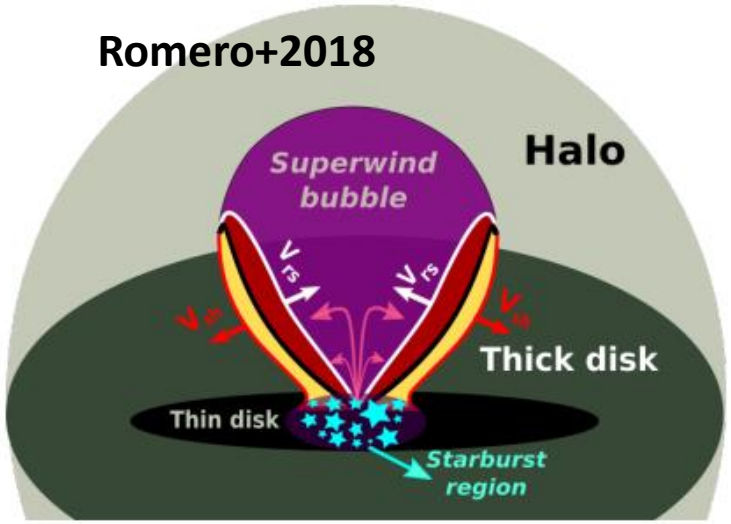
Werhahn+2021



Müller+2020



Romero+2018



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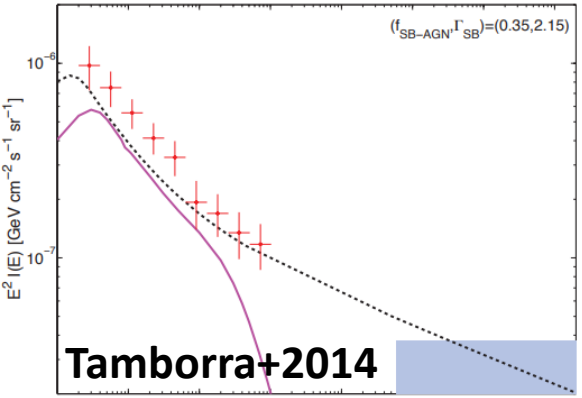

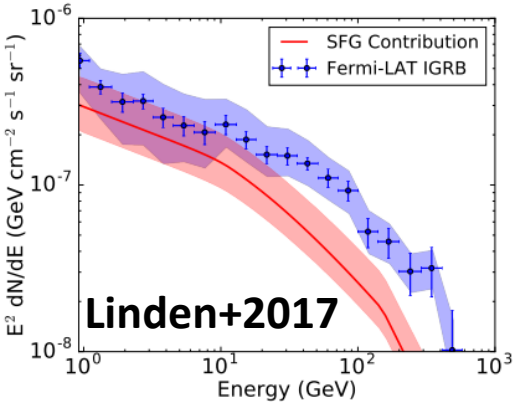

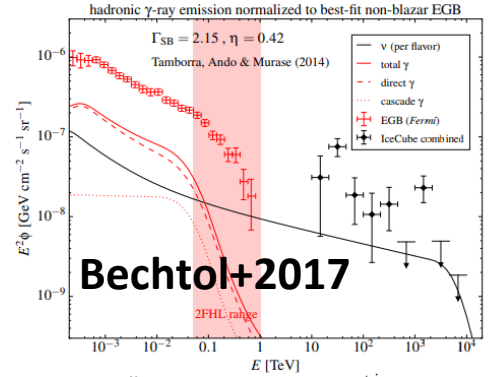

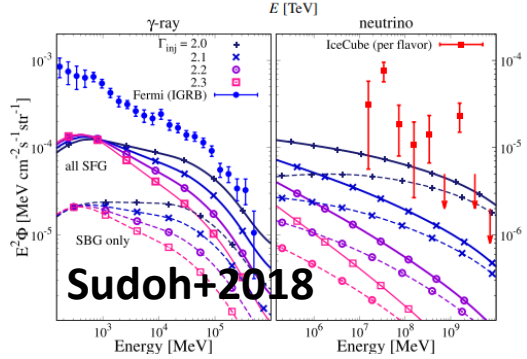

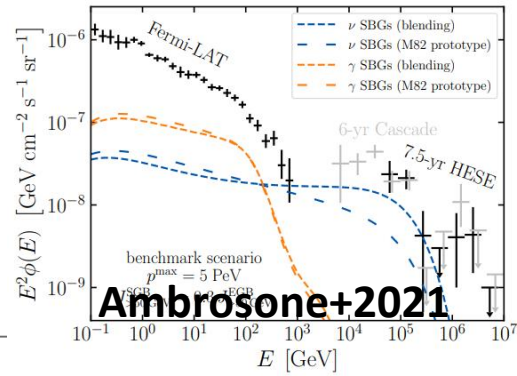

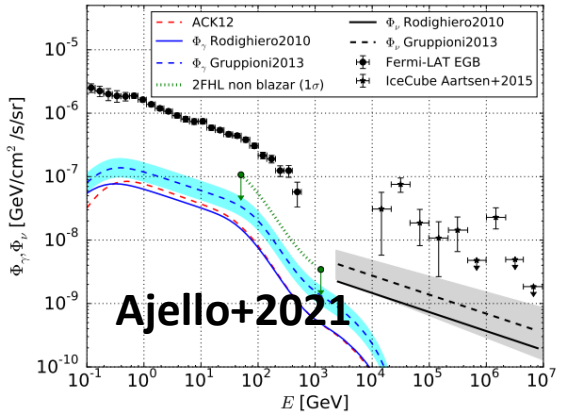

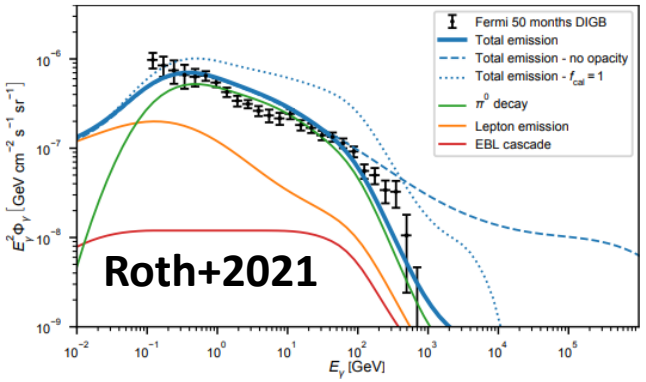

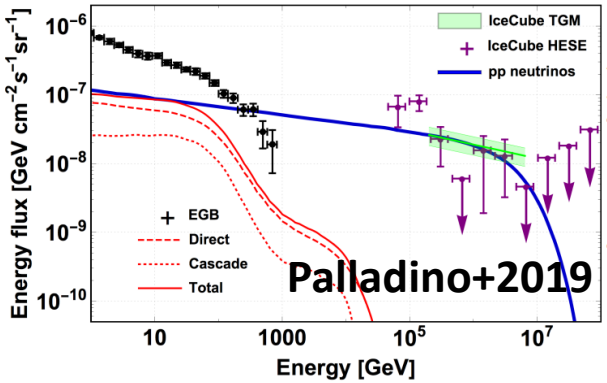

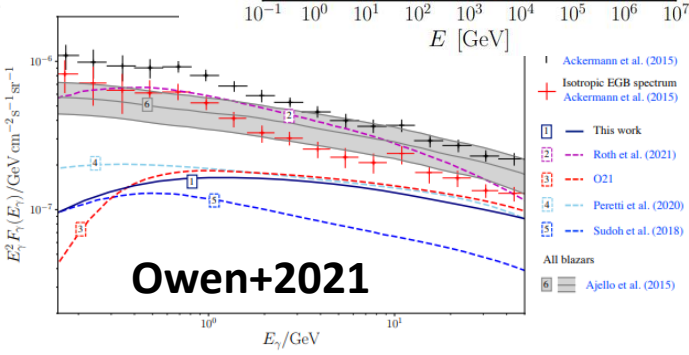

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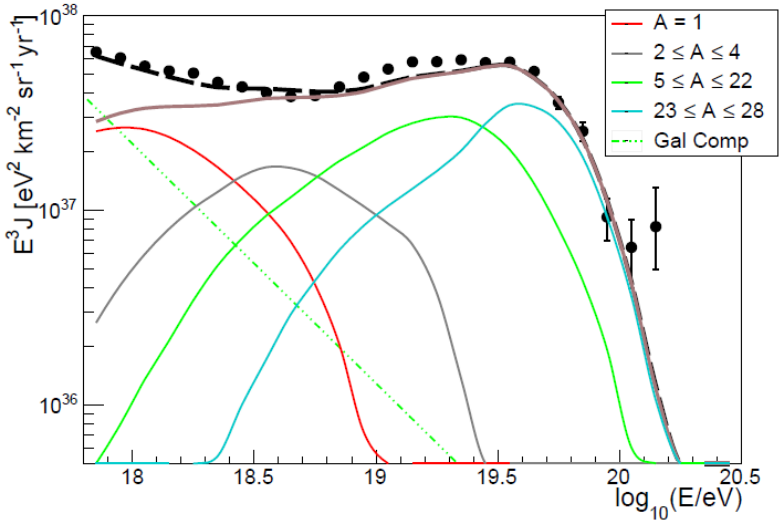
- What can accelerate UHECRs in SBGs?

Outlook and open questions

- Transport and diffusion: neutral medium?

Condorelli+2022 in prep.



What happens in the wind bubble?

Diffuse gamma and neutrino flux?

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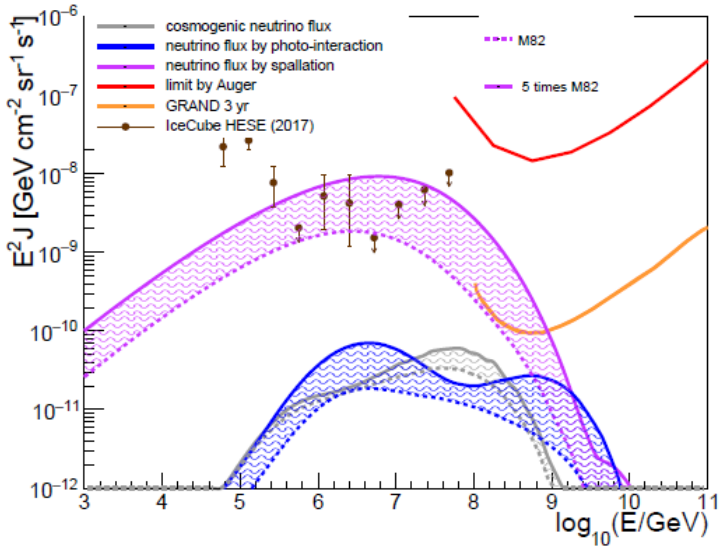
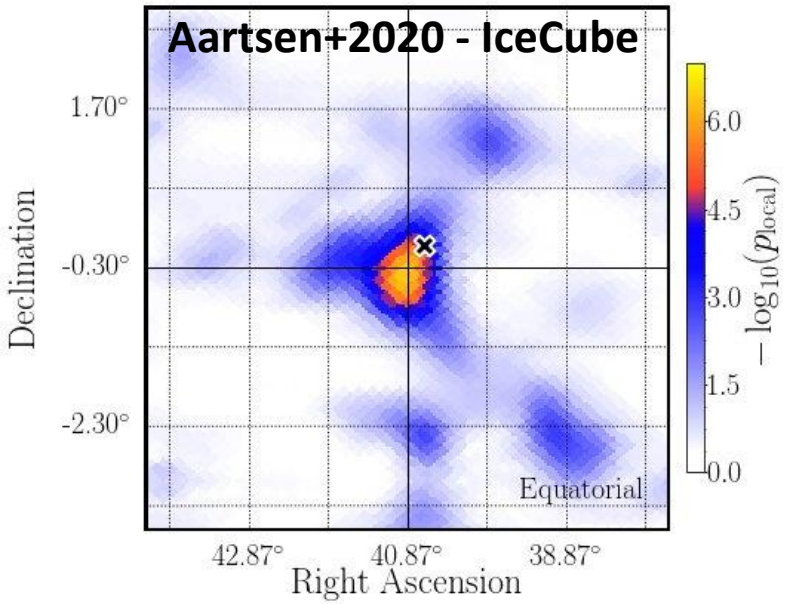


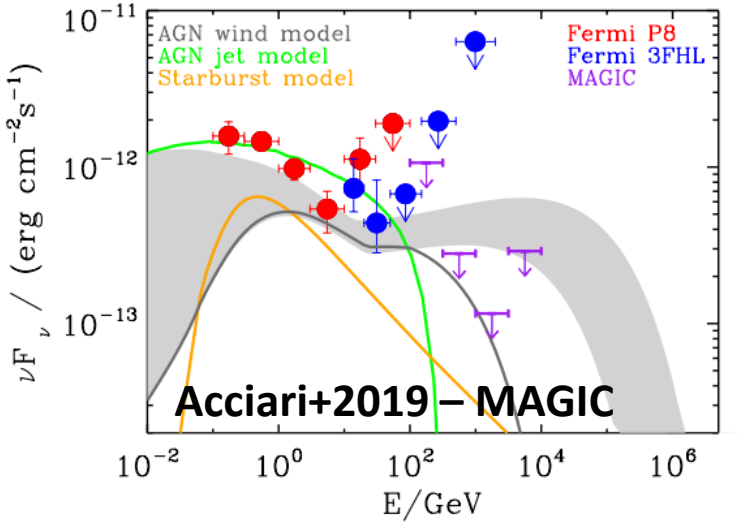
- What can accelerate UHECRs in SBGs?

Thanks for your attention!

Back up

NGC1068

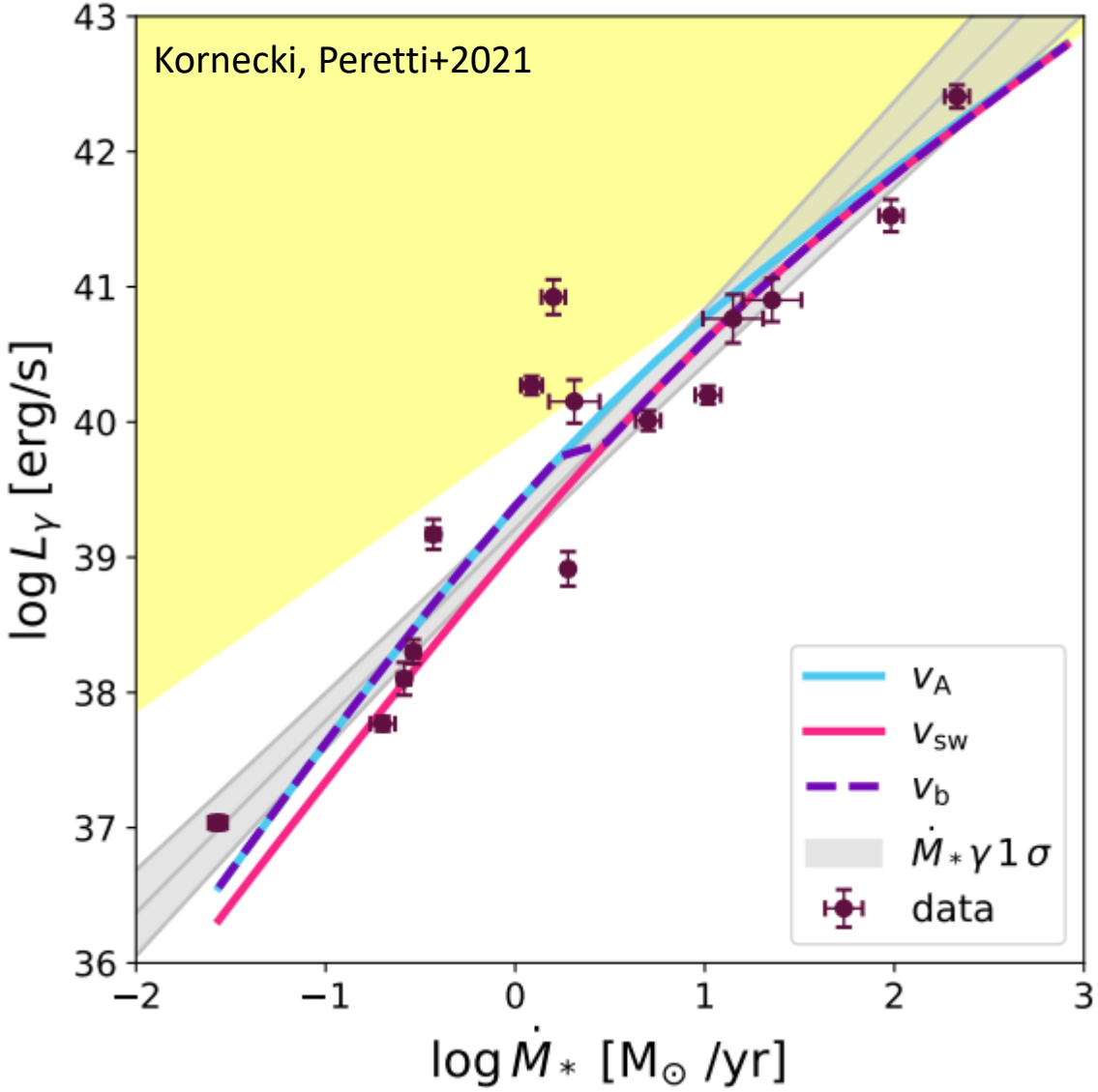


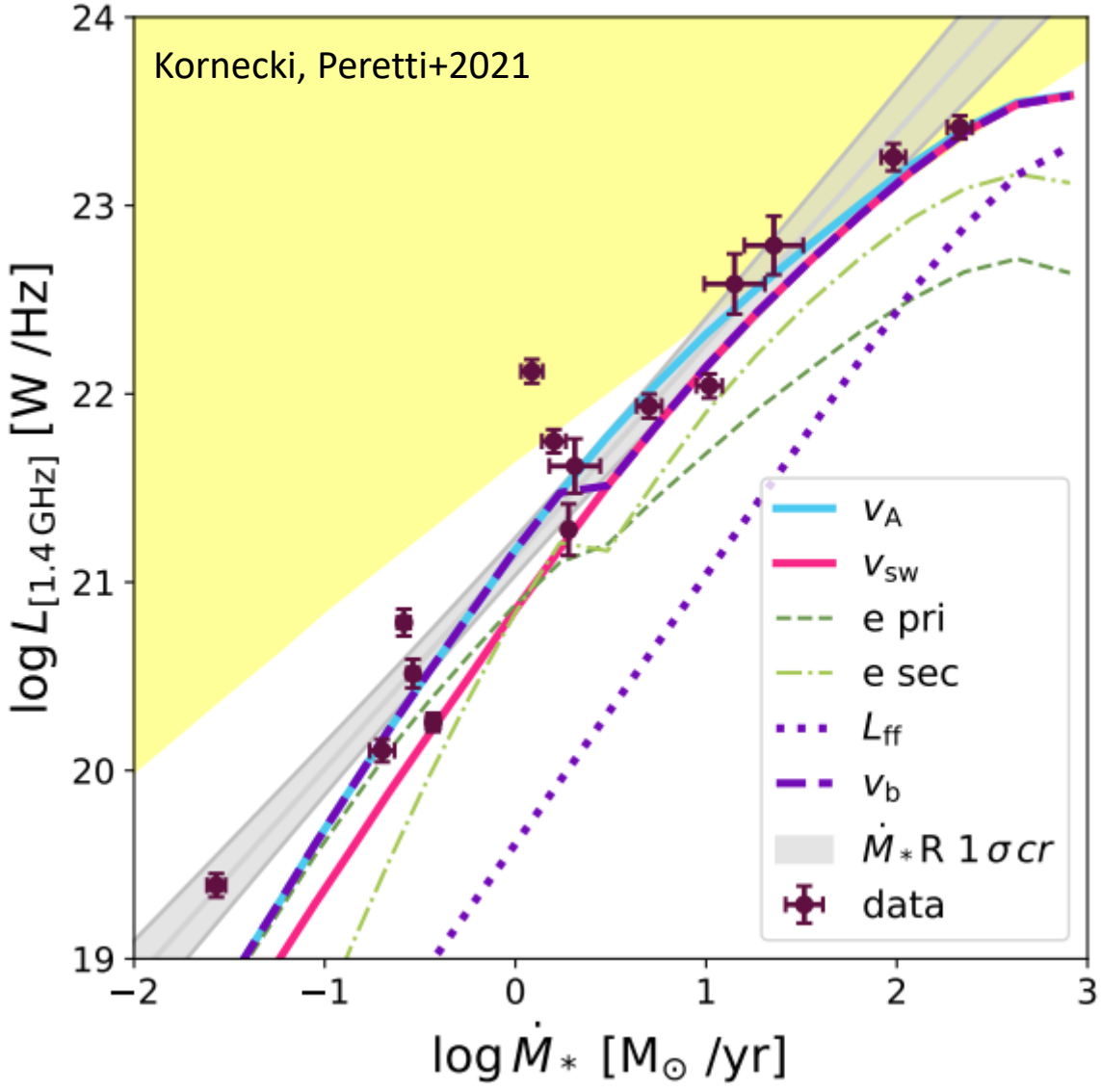


Indications of neutrino production at TeV in the nearby NGC1068 while gamma is limited below 10^2 GeV

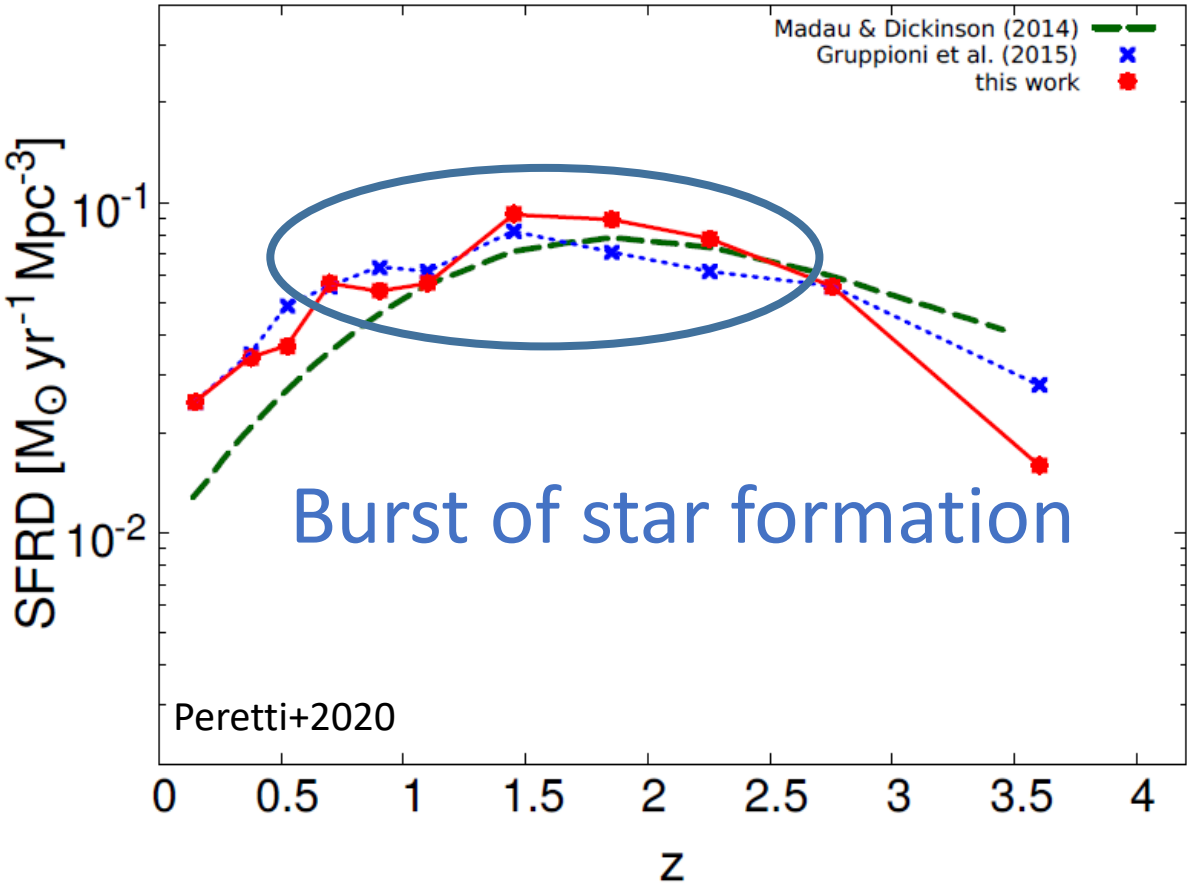
- Starburst emission?
- AGN jet? AGN wind?
- Other sources?

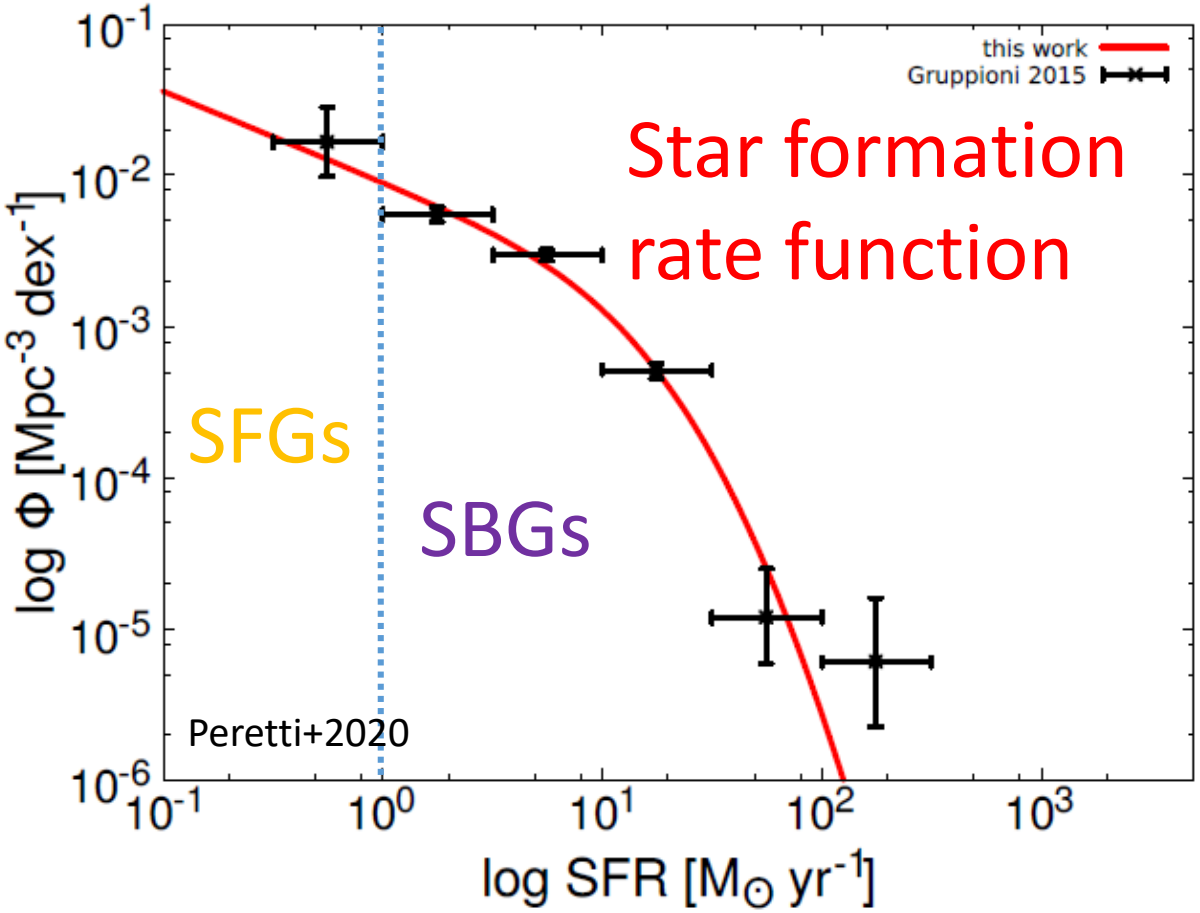
Leaky box model and L—SFR correlations





Starbursts as diffuse sources





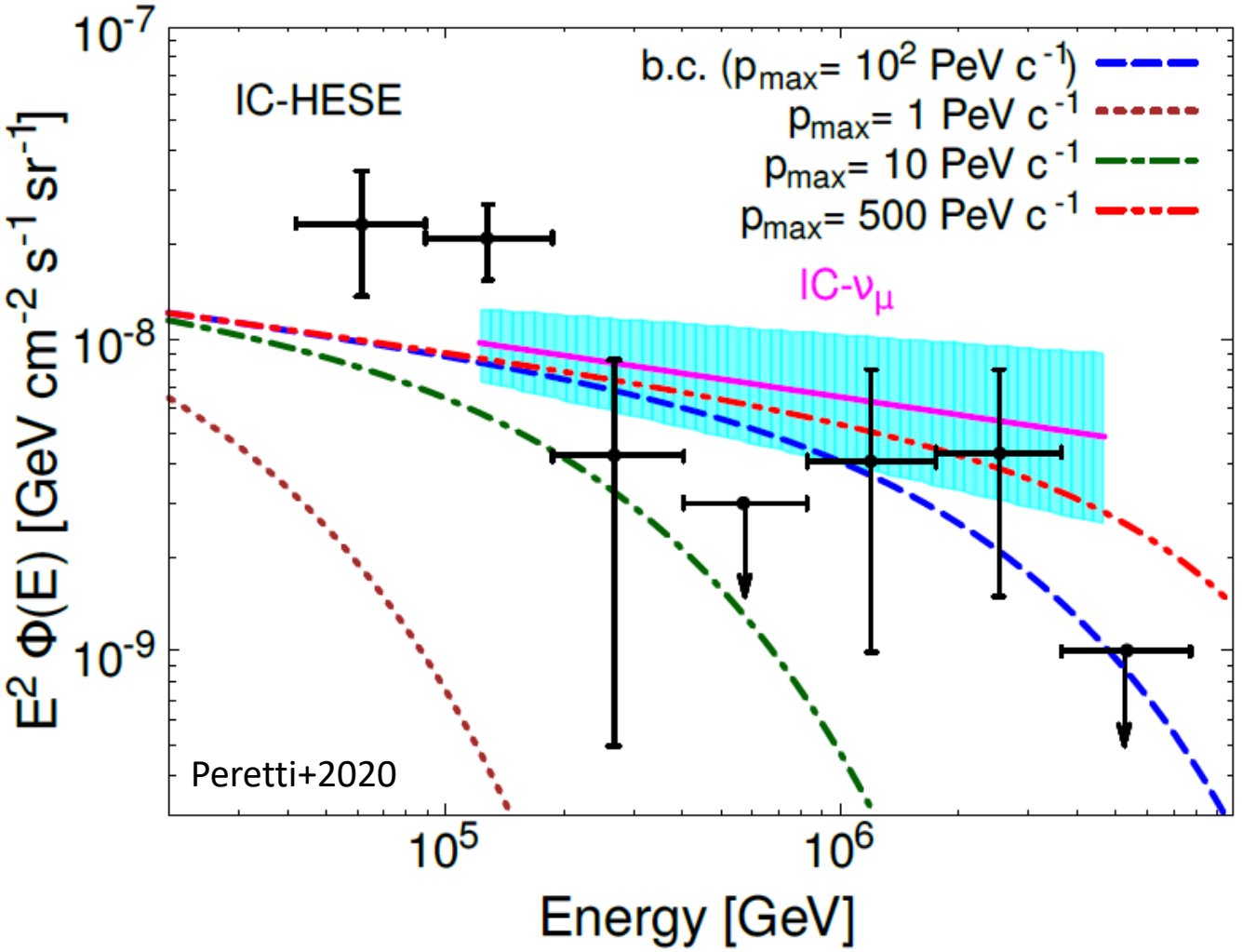
The issue of the maximum energy

Starburst contribution to IceCube neutrinos strongly depends on the maximum energy achievable in SBNi

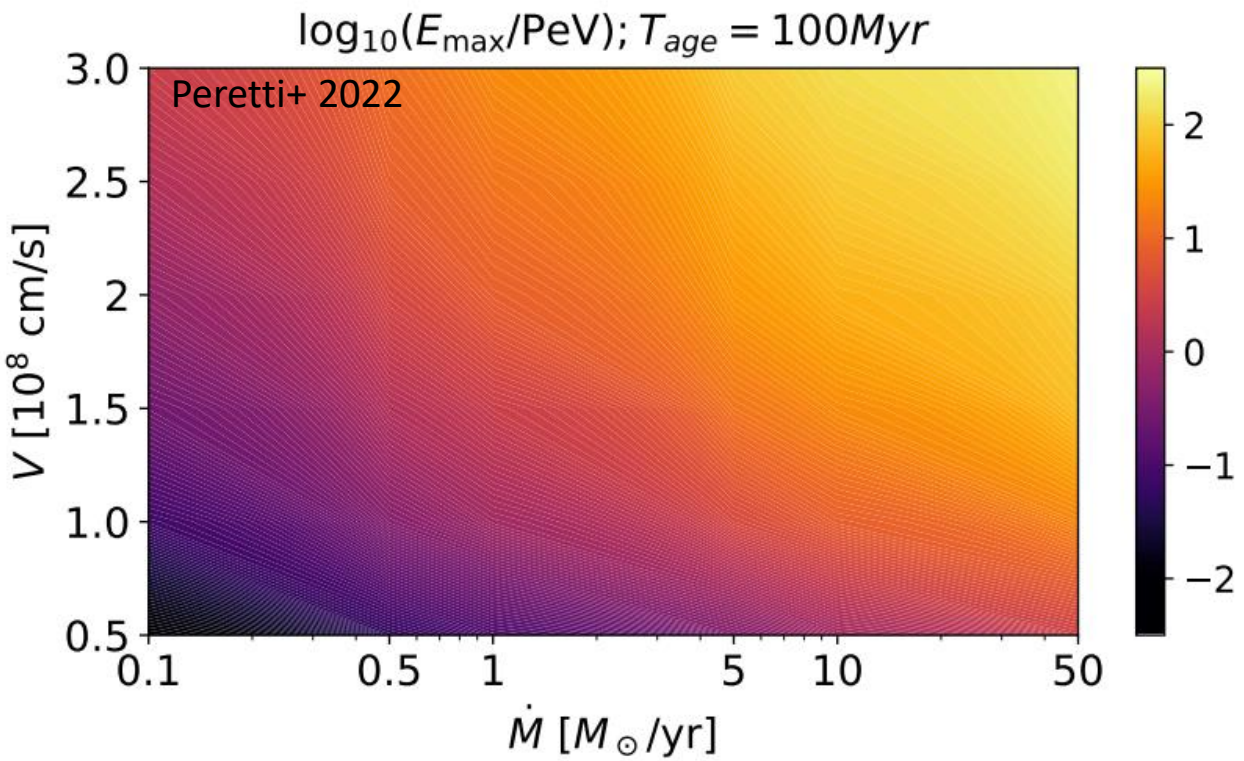
SNR in case of Bohm diffusion:

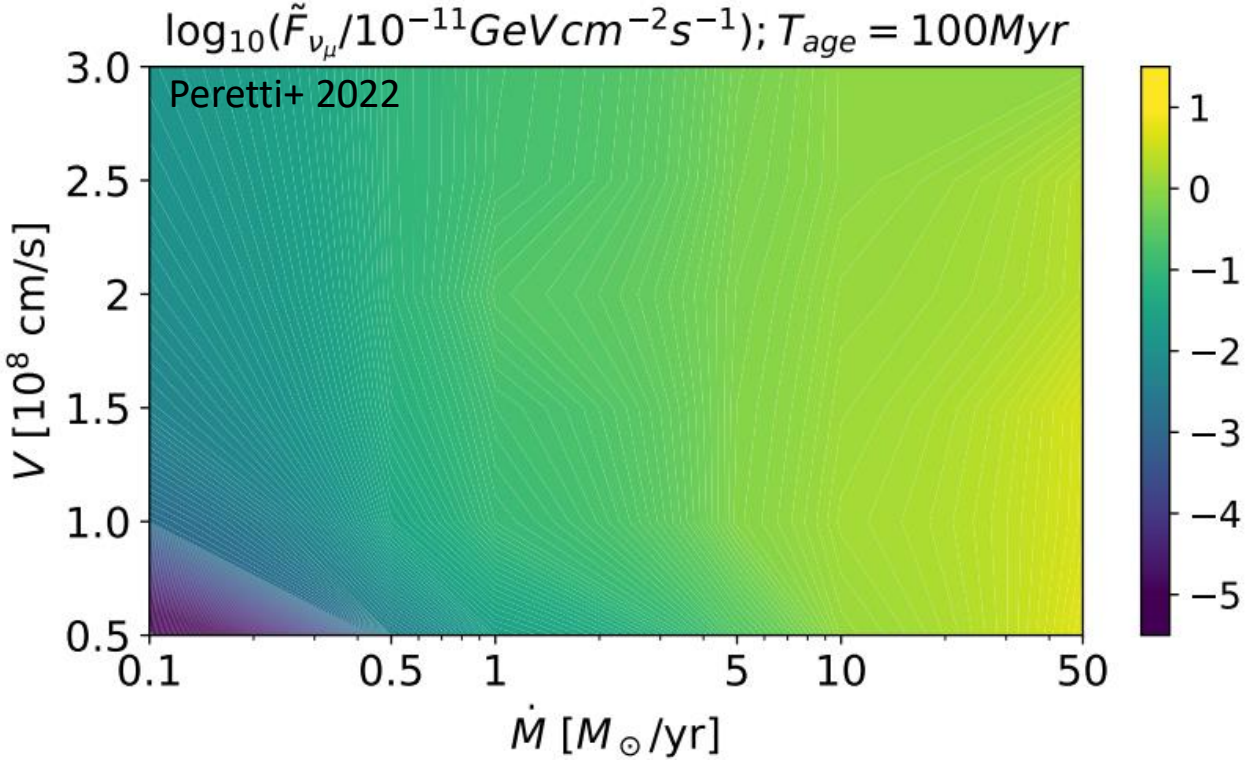
$$E_{max} = 30\ PeV\ \times R_3 u_4 B_{mG}$$

- Magnetic field amplification can allow reaching 10-100 PeV

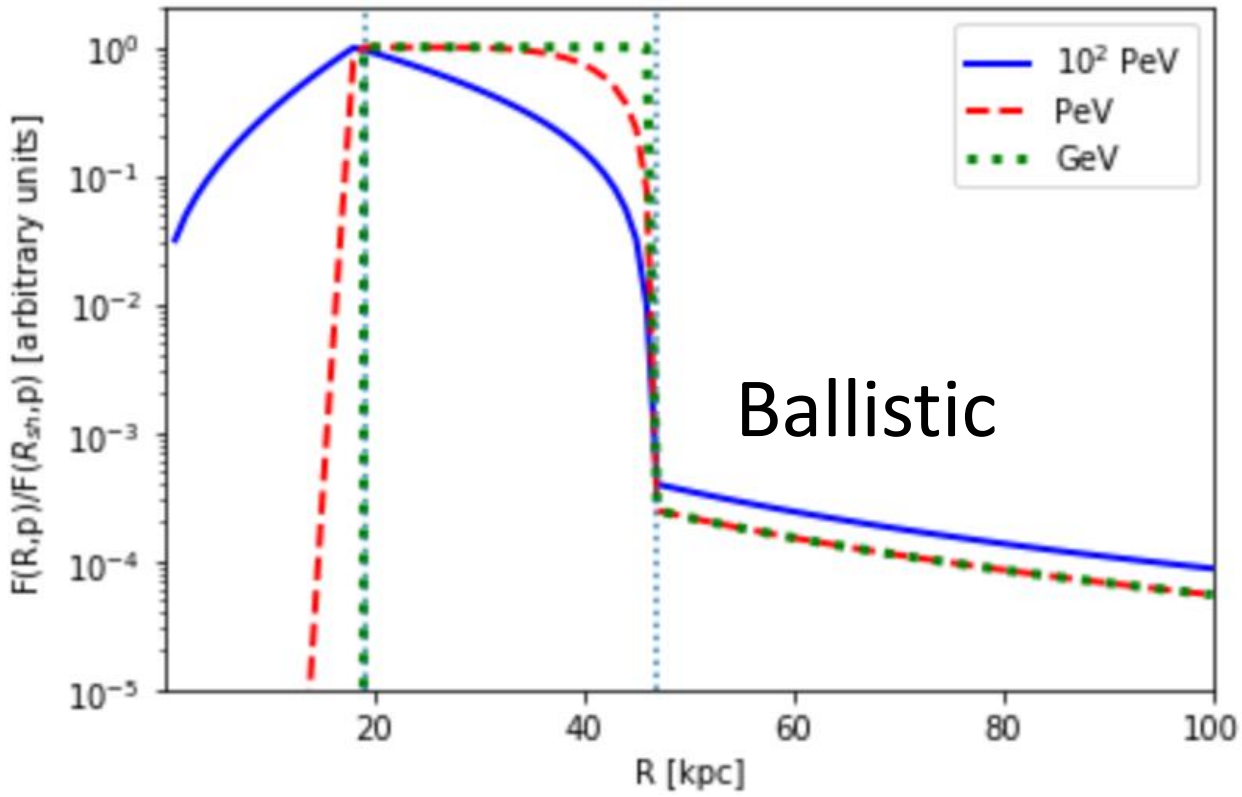


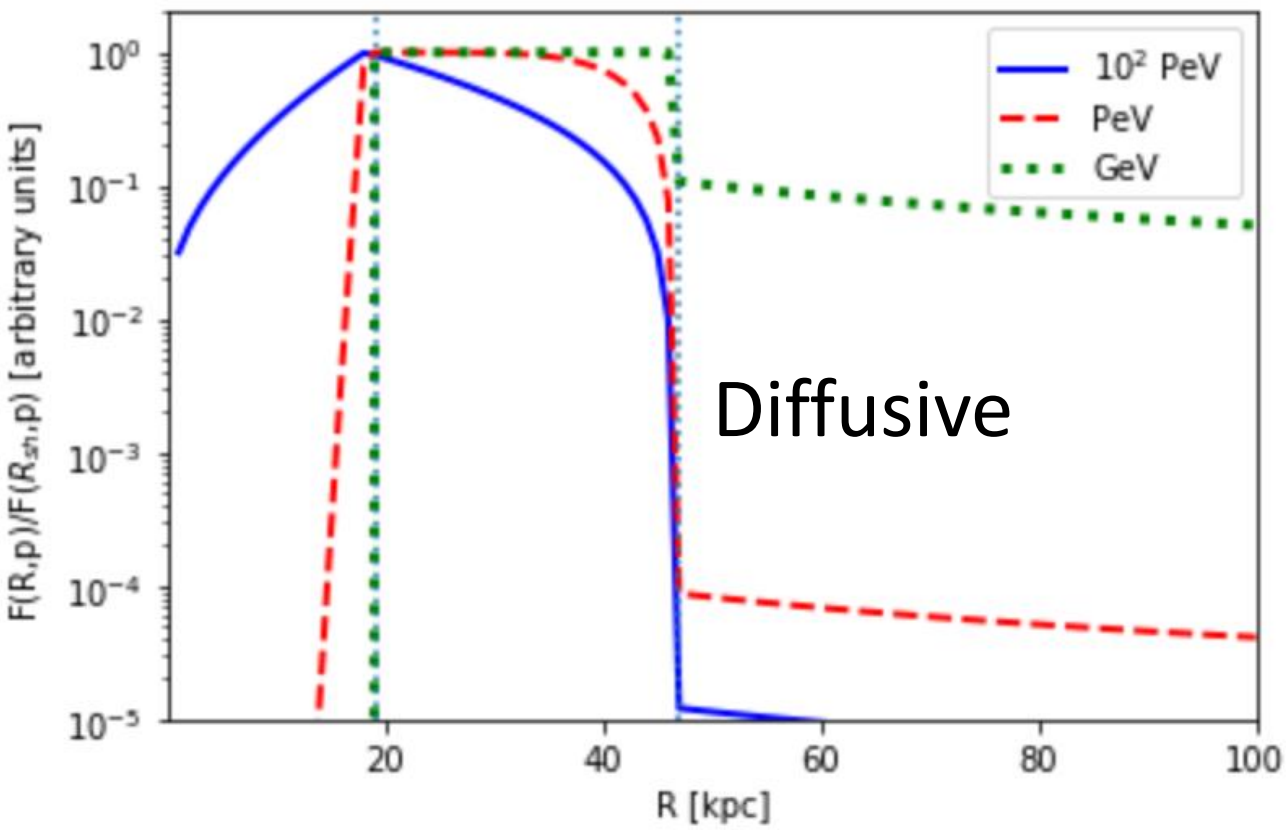
Maximum Energy & Luminosity



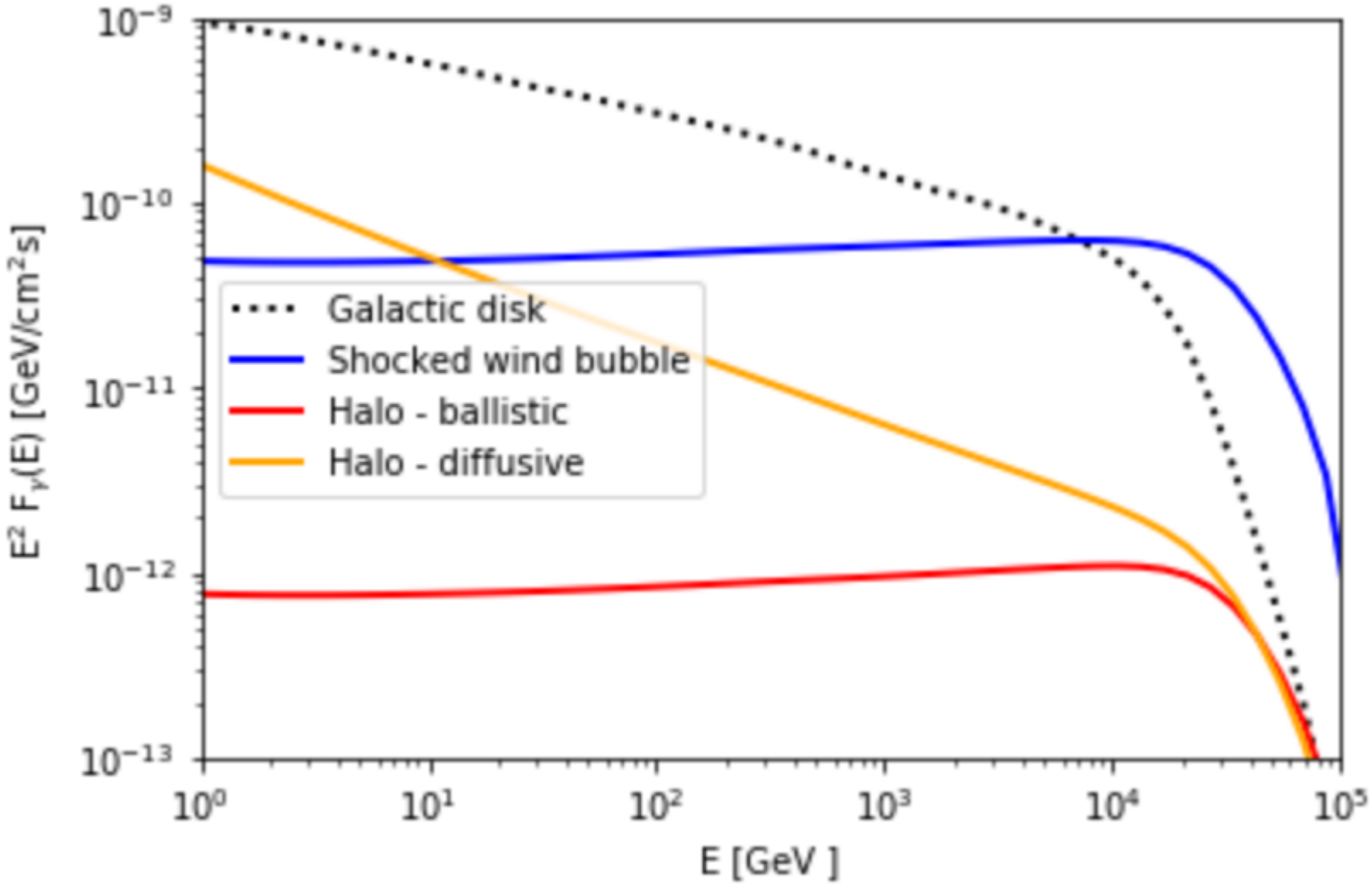


Starburst halo

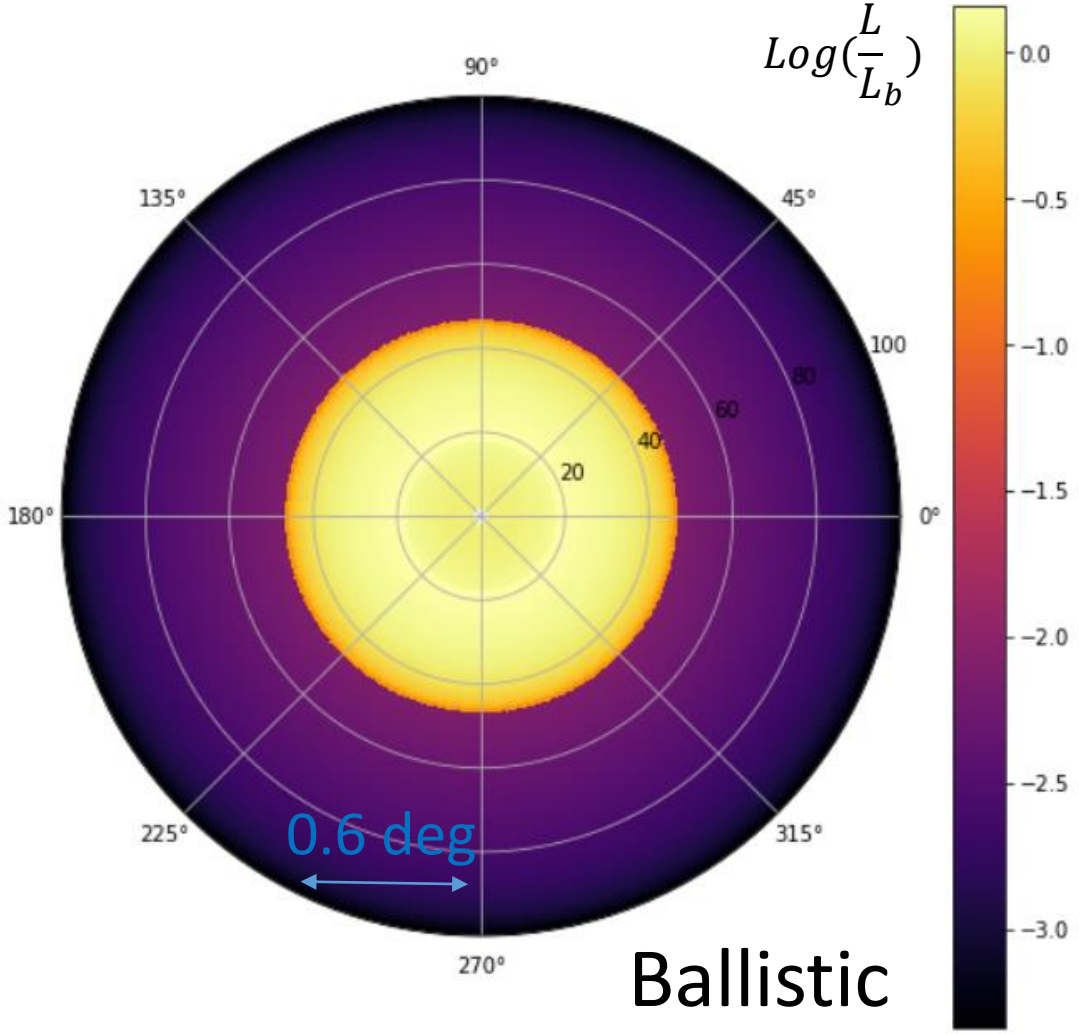




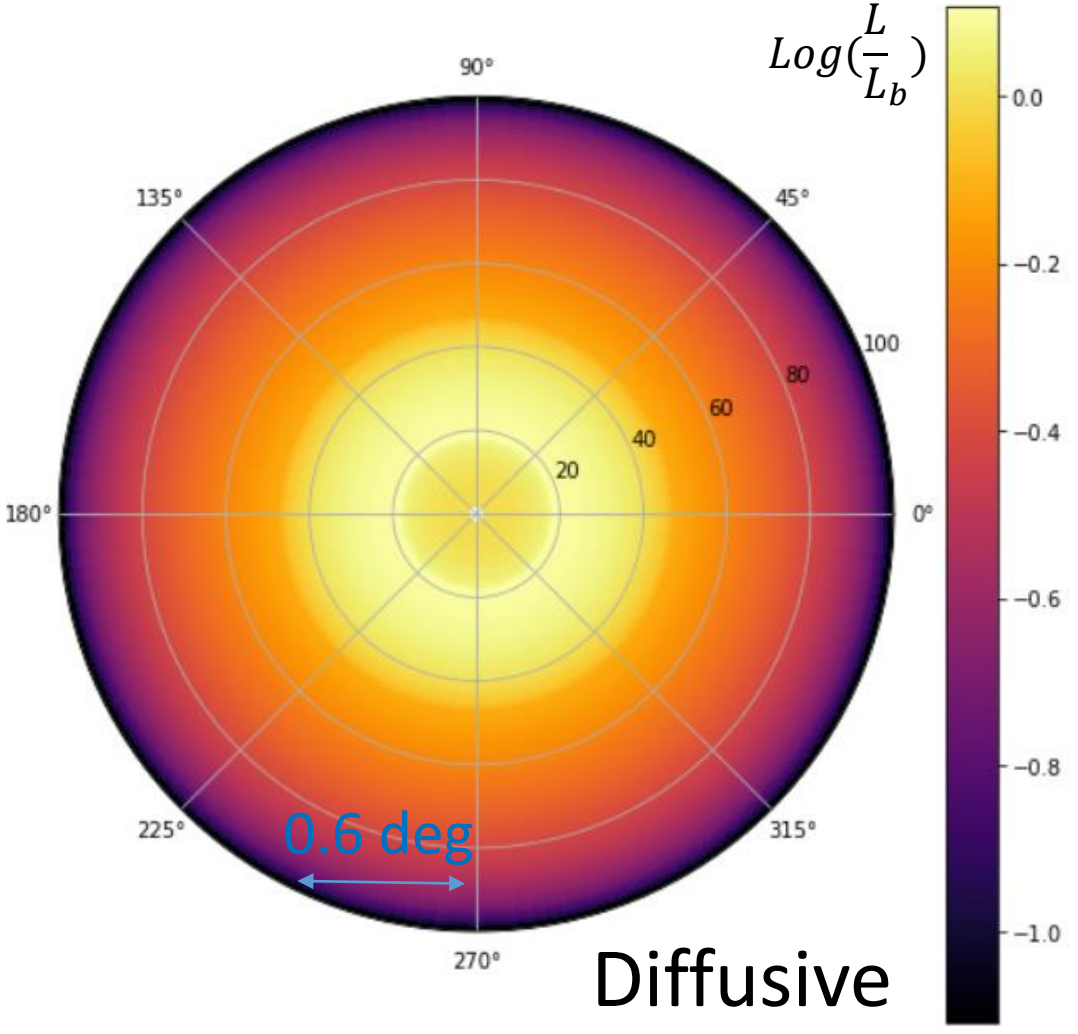
Starburst halo



Tracing the emission in the wind bubble – 1 GeV



Ballistic



Diffusive